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## **Energy and Resource Recovery from Wastewater Treatment: State of the Art and Potential Application for the Army and the DoD**

Victor F. Medina, Richard J. Scholze, Scott A. Waisner,  
and Chris S. Griggs

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# **Energy and Resource Recovery from Wastewater Treatment: State of the Art and Potential Application for the Army and the DoD**

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## Abstract

This report summarizes a study to assess energy and resource recovery from wastewater treatment and assess short- and long-term opportunities and impacts for the Army and the Department of Defense (DoD) in general. The organic material in wastewater contains inherent energy. The challenge is concentrating and recovering this energy. Several methods are available; of these, anaerobic digestion (either of the sludge, or directly applied to the wastewater using an Upflow Anaerobic Sludge Blanket or a similar reactor) is the most advanced and can be readily applied to existing military installations or to contingency operations.

Recovery of chemical products is another option for wastewater treatment. The most commonly recovered products are nutrients, in the form of nitrogen (N) and phosphorus (P). The simplest way is to recycle the collected and digested biosolids (sludges), either for direct soil application or by incorporation into compost. Resource recovery from wastewater may eventually include biopolymers that could make bioplastics or valuable nanometals that are increasingly found in consumer products.

Many of the energy recovery technologies and most of the resource recovery approaches (beyond simple biosolids recovery) require large-scale operations to be economically viable at this time. Wastewater treatment facilities that serve Army and other DoD installations tend to be relatively small, limiting the application of many approaches that might be practicable in the civilian sector. ERDC should focus research on technologies that could be economically applied to smaller treatment plants on the order of 3 to 10 mgd.

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# Contents

<b>Abstract .....</b>	<b>ii</b>
<b>Figures and Tables.....</b>	<b>v</b>
<b>Preface.....</b>	<b>vi</b>
<b>Acronyms .....</b>	<b>vii</b>
<b>1 Introduction.....</b>	<b>1</b>
Study Objective.....	1
Wastewater Treatment .....	1
Wastewater.....	1
Goals of Wastewater Treatment.....	2
Wastewater Treatment .....	2
Wastewater and the DoD.....	3
Drivers for Energy and Resource Recovery from Wastewater Treatment.....	4
Renewable Energy .....	5
Net Zero Installations.....	5
Net Zero Contingency Bases .....	6
Stability Operations.....	7
Force Reduction/Force 2025 and Beyond.....	7
Other Requirements.....	8
Energy Requirements for Wastewater Treatment.....	8
Energy Potential in Wastewater .....	8
Energy Conservation in Wastewater Treatment .....	9
Stakeholders/Partners .....	12
<b>2 Energy Producing Wastewater Treatment Approaches .....</b>	<b>13</b>
Anaerobic Digestion of Wastewater or Wastewater Sludge to Produce Biogas .....	13
Process Description .....	13
Anaerobic Sludge Digestion .....	13
Direct Methane Generation from Wastewater Treatment .....	14
Application to Installations .....	15
Application to Contingency Bases.....	17
Formation of Hydrogen Gas from Anaerobic Digestion .....	19
Challenges.....	20
Incineration, Gasification, and Pyrolysis of Residual Solids from Wastewater Treatment.....	21
Wastewater Treatment Producing Hydrogen Gas .....	22
Treatment and Energy Generation using Microbial Fuel Cells .....	23
Microbial Fuel Cells .....	23
Processes involved with MFC Reactions.....	23
Resistance.....	24

<i>Electrode and Membrane Materials</i> .....	25
<i>Passive Filtration Membranes</i> .....	26
<i>Electrical Production</i> .....	26
<i>Treatment of Municipal Wastewater</i> .....	26
<i>Issues with MFCs</i> .....	27
<i>Anaerobic Electrochemical Membrane Bioreactor (AnEMBR)</i> .....	28
Wastewater treatment-producing materials suitable for biofuel production .....	28
<i>Biofuels</i> .....	28
<i>Microbial Feedstocks for Biofuels</i> .....	28
<i>Wastewater Culturing of Microbial Feedstocks</i> .....	28
<i>Treatment of Wastewater with Biofuel Producing Organisms</i> .....	29
<i>Issues</i> .....	29
<b>3 Resource Recovery with Wastewater Treatment .....</b>	<b>31</b>
Nutrient recovery .....	31
Liquid Streams .....	32
Biosolids derived from sludge .....	33
High Value Chemical Nutrient Products .....	34
<i>Extractive Approaches</i> .....	35
<i>Source Separation</i> .....	39
<i>Environmental benefits of enhanced nutrient recovery</i> .....	40
<i>Wastewater-derived nutrients</i> .....	40
Plastics .....	41
Metals .....	42
Products from Digester Gas .....	42
<b>4 Discussion/Conclusions .....</b>	<b>43</b>
Deriving Energy and Resources from Wastewater fits Army Mission & Doctrine .....	43
Energy .....	43
<i>Anaerobic Digestion is the most applicable technology currently available</i> .....	43
<i>Assessment of other energy producing technologies</i> .....	45
Combining Technologies .....	47
Effects on Waste, Water, and Climate Change .....	47
Resource Recovery from Wastewater Treatment .....	48
<i>Sludge and sludge-derived products</i> .....	48
<i>Advanced Resource Recovery</i> .....	49
Economy of Scale .....	51
<b>References .....</b>	<b>52</b>
<b>Report Documentation Page</b>	

# Figures and Tables

## Figures

Figure 1. A generalized municipal wastewater treatment system.....	3
Figure 2. Generalized depiction of energy use versus treatment effectiveness for various wastewater treatment technologies. ....	11
Figure 3. Idealized schematic of an Upflow Anaerobic Sludge Blanket (UASB) Reactor. ....	15
Figure 4. Laboratory and pilot reactors used to study anaerobic digestion for treating FOB wastes (Medina et al. 2014b).....	18
Figure 5. Two examples of simple anaerobic digester reactors: covered lagoon (left) and bag reactors (right) (From Lansing and Moss 2010).....	19
Figure 6. A conceptual design of fuel cell energy and hydrogen production from sludge digestion (from Perez et al. 2006). ....	20
Figure 7. Generalized schematic of a microbial fuel cell with oxygen reduction at the cathode.....	23
Figure 8. Conceptual water purification design representing graphene oxide filtration and preparation (adapted from Mi 2014).....	49

## Tables

Table 1. Energy Estimates of Wastewater Treatment Processes for a 30 mgd Activated Sludge Plant (Owen 1982).....	10
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## Preface

The work reported herein was conducted at the U.S. Army Engineer Research and Development Center (ERDC), Environmental Laboratory (EL) (Vicksburg, MS) and Construction Engineering Research Laboratory (CERL) (Champaign, IL). The project was approved by the Center for the Advancement of Sustainability Innovations (CASI at CERL), and was funded from CERL and EL overhead resources.

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The report was prepared by Dr. Victor Medina and Scott Waisner of EL, and Richard Scholze of CERL. Peer review was provided by Dr. Heather Knoteck-Smith of ERDC-EL and by Dr. Veera Boddu of ERDC-CERL. At the time of publication of this report, Dr. Beth Fleming was Director, EL; Dr. Ilker Adiguzel was Director, CERL; LTC John T. Tucker III was Acting Commander of ERDC, and Dr. Jeffery P. Holland was ERDC Director.



## Acronyms

AEC	Army Environmental Command
AERTA	Army Environmental Requirement Technology Assessment
AFCEC	Air Force Civil Engineering Center
ASAALT	Office of the Assistant Secretary of the Army, Acquisitions, Logistics and Technology
BTU	British Thermal Units
CASI	Center for the Advancement of Sustainability Innovations
CB	Contingency Base
CBITEC	Contingency Base Integration and Technology Evaluation Center
CERL	Construction Engineering Research Laboratory
COD	Chemical Oxygen Demand
COL	Colonel
DoD	Department of Defense
EL	Environmental Laboratory
ERDC	Army Engineer Research and Development Center
EP, EPE	Environmental Processes Division, Environmental Engineering Branch
FOB	Forward Operating Base
Ft.	Fort
FY	Federal Fiscal Year (Typically from 01 October to 30 September)
g, Kg, mg, µg	gram, kilogram, milligram, microgram
gal	gallon(s)
ISAF	International Security Assistance Force
J, KJ, MJ	Joules, kilojoules, megajoules
kW, MW	kilowatt(s), megawatt(s)
L, mL	liter(s), milliliter(s)

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m, mm, $\mu$ m	meter, millimeter, micrometer
mgd	million(s) gallons per day
MSCoE	Army Maneuver Support Center of Excellence
NAVFAC	Naval Facilities Command
NZB	Net Zero Base
NZI	Net Zero Installation
OACSIM	Office of the Assistant Chief of Staff for Installations Management
ODASA	Office of the Deputy Assistant Secretary of the Army (Installations, Energy and Environment)
SCoE	Army Sustainability Center of Excellence
sec	second
TECD	Technology Enabled Capability Demonstration
UASB	Upflow Anaerobic Sludge Blanket
US	United States
USACE	United States Army Corps of Engineers
USALIA	United States Army Logistics Innovation Agency
USDOA	United States Department of the Army
USEPA	United States Environmental Protection Agency
USMC	United States Marine Corps.
W, kW	Watt(s), kilowatts
WRRF	Water Resource Recovery Facility
WTE	Waste to Energy
WWTP	Wastewater treatment plant

# 1 Introduction

## Study Objective

In the past, the primary objective of wastewater treatment has been to treat it so it could be safely discharged, reducing human health and environmental effects to acceptable levels and allowing for natural purification (Hammer 1986). The United States Environmental Protection Agency (USEPA) has referred to the 9.5 trillion gallons of wastewater discharged annually in a new paradigm, as "water that is wasted" (Capuco 2013). It is now being recognized that wastewater actually has beneficial resources (energy and chemical resources), and new technologies are being developed that allow for these resources to be utilized or exploited while still achieving treatment goals. The objective of this study is to explore new wastewater treatment approaches that allow for energy and resource recovery; a secondary objective is to evaluate how these might fit into wastewater treatment for the Army and the Department of Defense (DoD) in general.

## Wastewater Treatment

### Wastewater

Wastewater is any water that was removed from its natural source and had its quality adversely affected by man. There are several types of wastewater that the Army and other DoD entities must manage. Municipal wastewater is produced from residential and light commercial activities, such as office activities, and also may include surface runoff, depending on the sewer conveyance in place. Domestic wastewater focuses strictly on wastewater produced from household use. The DoD is exploring further wastewater separation to promote more water reuse opportunities. In the United States, blackwater is water collected from toilet usage and kitchen wastes. At contingency bases, blackwater is strictly toilet wastewater. Gray water is generally considered to be wastewater that excludes toilet usage, including shower water and laundering in most states; a few states classify kitchen wastewater with gray water. All other non-industrial wastewaters are classified as gray water. The Army also has strong interests in industrial wastewaters from the production of weapons or key equipment, and these can include organic chemicals such as nitroaromatics and other nitrated

organic compounds from explosives production, metals from the production of small arms ammunition or armor, and nanomaterials. This report will focus primarily on municipal wastewater, but the findings could be applicable to other situations. These applications would be valuable to ERDC for addressing challenges associated with Net Zero Energy installations and making contingency bases more efficient.

### **Goals of Wastewater Treatment**

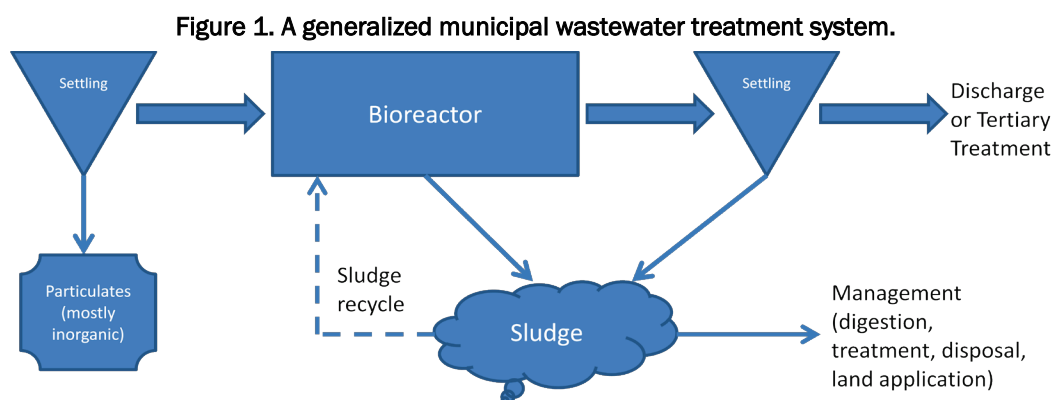
With few exceptions, the goal of wastewater treatment is not complete purification of the affected water. Rather, the goal is to allow safe discharge into a receiving water body (lake, river, or ocean) that allows for natural processes to purify the water while protecting human and ecological health (Hammer 1986). Typical goals of wastewater treatment are:

- reduction of volatile organic loading into the receiving waterbody, to reduce oxygen depletion and allow for a reasonable application of natural purification to occur;
- control of nutrients, particularly nitrogen (N) and phosphate (P) forms, to reduce excess algal growth;
- reduction of pathogenic and enteric microorganisms; and
- reduction or elimination of toxic chemicals or metals: this may also be controlled by limiting these materials in the wastestream.

With increasing stress on water resources throughout the world, there is increasing interest and implementation of enhanced treatment to allow reuse of municipal wastewater, which is practiced in some forms in many water-short states, such as California, Arizona, Texas and Florida. The Army has also taken a strong interest in water reuse (U.S. DoD 2013).

### **Wastewater Treatment**

As the bulk of the wastewater constituents in wastewater are organic, the primary means of treating wastewater involves biological processes (Hammer 1986, Henze et al. 2002). A typical plant schematic is shown in Figure 1. Water entering the plant is generally first treated by some means to remove large materials, like screening and sedimentation. This is followed by a biological process to degrade organic materials and incorporate nutrients. Because the biological process promotes the growth of microbial biomass, this is usually removed by a second sedimentation process. The removed biomass forms a sludge, which also must be managed as part of the treatment process.



There are a myriad of options available to fill the role of “Bio-Reactor.” Most municipal treatment systems are aerobic, although there are anaerobic possibilities. Aerated suspended growth bioreactors are reactors that are vigorously aerated, allowing for vigorous microbial growth to be suspended in the wastewater. Fixed film bioreactors have solid media, which support microbial growth. Trickling filters are traditional fixed film reactors in which growth is supported on large rocky material or plastic media. Biomembranes are a more recent development and can concentrate biological growth, resulting in smaller reactors. Both suspended growth and fixed film bioreactors generate sludge associated with the growth of microorganisms that must be managed.

A common practice in wastewater engineering is to use sludge recycling, in which a portion of the sludge is recycled back into the bioreactor, allowing substantial enhancement of the degradation of the organic material. The most common wastewater treatment process used in the United States is Activated Sludge, which is a combination of aerated suspended growth with sludge recycling.

### Wastewater and the DoD

The DoD has over 5,000 sites throughout the world. Populations on these sites can vary substantially, and many smaller properties have zero populations. However, based on the 2007 DoD Base Structure Report, there are 62 installations with populations >10,000, and 11 with populations >30,000. (U.S. DoD 2007, sites counted from data tables in report). Three installations, Fort Hood, Fort Bragg, and Naval Station Norfolk, have populations of 60,000 or more. These concentrations of people can represent a large proportion of the overall population in the areas that they are located in. Because of this, many of the larger installations (with

populations of 10,000 or more) currently operate their own wastewater treatment systems (which may be operated by contract). Wastewater generation can vary quite a bit depending on uses and on what water discharges actually go into the sanitary sewer system - and can range between 50 gal (190 L) to 250 gal (950 L) per day (Hammer 1986). The U.S. DoD (2004) estimates that the average wastewater generation per person in a U.S. installation is 100 gallons (378 L) per day. Perez et al. (2006) provides design and actual wastewater rates for two Army installations. Ft. Stewart (GA) had a design capacity of 9 mgd and a current flow rate of 5 mgd. Ft. Lewis (WA) had a design capacity of 7 mgd and an actual rate of 3.5 mgd.

Wastewater is also a concern for the U.S. Army and other DoD entities during contingency operations. Untreated discharges can result in disease to the neighboring population or even to the base itself. Lagoon treatment is a low technology, low-cost means of providing sanitation, but can be overloaded and can become a problem itself, especially when the design is overwhelmed by a rapidly expanding population. Deployable treatment systems can provide good treatment, but require energy to operate. The U.S. Army has been searching for energy neutral systems to provide treatment for contingency operations.

### **Drivers for Energy and Resource Recovery from Wastewater Treatment**

The Army and the other DoD entities consume large amounts of energy to defend the United States and maintain mission readiness. According to congressional testimony by Mr. Michael Breen, the Executive Director of the Truman Project and Center for National Policy, the U.S. military is the largest institutional consumer of energy in the world (Erwin 2014). Yet, energy sources are frequently unreliable and subject to conflict. By reducing energy use and finding new sources of energy, the military can improve its mission readiness. The DoD has recognized that water and energy are strongly linked, and that there are opportunities to recover energy from more efficient uses of water resources (U.S. DoD 2013). In addition, the Secretary of the Army listed “Develop Effective Energy Solutions” as one of his top 10 priorities for FY14 (Secretary of the Army 2014).

Crowley et al. (2007) studied energy issues for the DoD. A waste-to-energy workshop that coupled researchers, vendors, and Army installation operators and policy makers was conducted in 2008 (Holcomb et al. 2008).

Both of these sources recommended increasing energy efficiency and studying and implementing alternative energy sources. The studies also recommended making energy a top research and development priority.

### **Renewable Energy**

In 2013, the DoD estimated that it was obtaining 9.6% of its energy through renewable sources (both electrical and non-electrical forms) (U.S. DoD 2013). Title 10, United States Code 2911(e)(2) requires the DoD to reach 25% renewable energy at its installations and facilities by 2025. The DoD has made the decision to prioritize the installation of renewable energy capabilities at its facilities, as opposed to simple procurement of energy from renewable sources. Even with increases in energy efficiency, it will be necessary to develop new renewable sources. Obtaining energy from wastewater can contribute to this goal.

### **Net Zero Installations**

The U.S. Army Net Zero Installation (NZI) Strategy was announced in 2010 (ODASA 2010). The main goal of this strategy is to integrate sustainability practices at the installation level to preserve the flexibility to operate in constrained circumstances, either economical or environmental. Initially, Net Zero focused on 20 demonstration installations, which were to strive to meet Net Zero goals by the year 2020. These demonstrations are continuing; however, in 2014, the Army announced that all Army installations were to strive to meet Net Zero goals as best as they can while still meeting mission requirements and while operating in a fiscally responsible manner (McHugh 2014). The United States Air Force has also adopted Net Zero and is developing an implementation strategy.

Net Zero is divided into three efforts: Net Zero Energy, Net Zero Water, and Net Zero Waste. A Net Zero Energy installation is defined as an installation that produces as much energy on site as it uses. A Net Zero Water installation limits the consumption of fresh water resources and returns the water back to the same watershed. A Net Zero Waste installation reduces, reuses, and recovers waste streams, converting them to resource value with virtually zero wastes sent to landfills.

The production of energy from wastewater treatment would primarily focus on Net Zero Energy, as it would allow the installation to reduce the net energy lost due to energy production, and could even allow for net total

energy production. Renewable energy is considered an important part of meeting Net Zero energy goals (ODASA 2013). Resource recovery from wastewater treatment primarily addresses Net Zero Waste. However, beyond the primary goals, these processes also provide opportunities to meet other Net Zero goals as well. For example, additional treatments to recover energy could allow for solid waste recovery. Consider sludge digestion (see below), which provides additional treatment that allows the sludge to be beneficially reused as a soil amendment, either directly or after composting. Alternatively, recovered energy could be used to power additional treatment, allowing the treated wastewater to be beneficially reused, which then could reduce energy needs by reducing the need for the conveyance of raw water.

### **Net Zero Contingency Bases**

During both operations Enduring Freedom (Afghanistan) and Iraqi Freedom (Iraq), the United States and its allies maintained a series of base camps and forward operating bases (FOBs) to support operations. These bases required fuel to properly function, and fuel convoys were targeted by our adversaries. Attacks on fuel convoys were the greatest single source of casualties in both conflicts, resulting in thousands of casualties (Erwin 2014). Reducing energy and other resource requirements for contingency bases of all sizes is considered an important goal for the U.S. Army, which has led to the development of the Net Zero Contingency Base philosophy. The processes of reduction, repurposing, and recycling are referred to as diversion, and NZI prioritizes diversion over waste to energy (WTE). However, a contingency base might benefit from a waste-to-energy focus (Medina et al. 2013), as diversion opportunities would likely be more restrictive in a contingency operation.

Net Zero Contingency Bases is similar to Net Zero installation in that it also consists of Energy, Water, and Waste, and that the goal is to promote much more efficient resource use. However, there are some different drivers in NZB. Delivery costs of fuel, water, and resources can be 10, 100, even 1000 times more than those for U.S. Installations, particularly if force protection costs are factored in (Noblis 2010, Siegel et al. 2008). This cost differential could allow for more favorable conditions in determining cost-effectiveness of new technologies and approaches. Furthermore, reducing soldier casualties is also a goal beyond just costs. However, this can be counterbalanced by the need to keep base camp operations simple and by manpower needs. If a technology requires even one additional



person to operate and maintain it - that might be too much in many base camp scenarios.

### **Stability Operations**

During Operations Enduring Freedom and Iraqi Freedom, the U.S. Army operated largely under the doctrine of Full Spectrum Operations. Since 2010, this doctrine has been updated and superseded by Unified Land Operations (DOA 2011). Both doctrines have stability operations as an integral part of their philosophy, stability operations involves supporting local populations in terms of environmental and health protection, establishing a stable environment for the development of business, providing basic services and housing, and undertaking any other activities associated with stabilizing the local environment. In a case of war, it is likely that energy and wastewater treatment would be important services to develop and maintain.

Stability operations were conducted during both Enduring and Iraqi freedom, and some of these involved energy generation from wastewater and other wastes. Jones (2011) describes a biogas plant constructed near Kabul, Afghanistan, as part of an International Security Assistance Force (ISAF) program to improve environmental conditions, provide construction jobs, provide operational jobs, and produce biogas for energy. This biogas plant operated primarily on animal wastes, which were common in the area. In addition to simply operating, the biogas plant was intended to provide training for other installations planned in Afghanistan. In a similar manner, anaerobic digestion was planned for managing human wastes (blackwater) throughout Afghanistan, led by MAJ Edward Mears (Maryniak 2011). It is logical to assume that such plants could be viable transitional technologies in many places where the Army must operate in the future.

### **Force Reduction/Force 2025 and Beyond**

The Army and the DoD are in the beginning of a force reduction, which is necessary due to reductions in funding. Force 2025 and Beyond is a planning process with the goal of maintaining or even increasing capabilities, even as these reductions occur (O'Conner 2014). Reducing acquisition and logistical costs and manpower requirements are a key part of achieving this goal. Waste to energy and recovery of useful materials from

wastewater treatment could provide substantial opportunities to reduce the need for energy and resources, enabling the Army to do more with less.

### **Other Requirements**

The U.S. Army Concept Capability Plan (CCP) for Army Base Camps in Full Spectrum Operations for the Future Modular Force 2015 – 2024 calls for increased flexibility in base camp operations through sustainable and adaptable designs. Army Environmental Requirement Technology Assessment (AERTA) PP-5-06-02, Zero Footprint Camp, calls for the use of materials currently managed as solid waste and wastewater as potential resources (OACSIM 2012). AERTA MM-10-07-02 (Avoidance of Risk During Contingency Operations) specifies limiting environmental damage from military operations. This project also addresses technology gaps in Technology Enabled Capability Demonstration (TECD) 4a “Sustainable Logistics-Basing.”

## **Energy Requirements for Wastewater Treatment**

Wastewater treatment is generally energy intensive. Most wastewater treatment plants are designed to be largely gravity flow, but aeration can consume a lot of energy, as well as produce significant quantities of sludge handling and processing. It is estimated that 3% to 7% of the energy consumed in the U.S. is for wastewater treatment (Logan 2004, McCarty et al. 2011, Xie 2011). For a traditional activated sludge treatment system with anaerobic sludge digestion, the average energy usage has been estimated at  $2 \times 10^6$  J/m<sup>3</sup> water treated (McCarty et al. 2011, Xie 2011). (The authors will report energy in the units originally given in the source, but will show it in joules in parentheses).

### **Energy Potential in Wastewater**

McCarty et al. (2011) estimated energy in municipal wastewater by relating it to an estimated chemical oxygen demand (COD) of 0.5 kg/m<sup>3</sup>. Using a theoretical estimate of  $1.47 \times 10^7$  J/kg of COD (assuming complete oxidation to CO<sub>2</sub> and H<sub>2</sub>O), the energy density of water was estimated at  $0.74 \times 10^7$  J/m<sup>3</sup>. Similarly, Heidrich et al. (2011) estimated energy densities of  $1.69 \times 10^7$  J/m<sup>3</sup> for a mixture of domestic and industrial wastewater and  $0.76 \times 10^7$  J/m<sup>3</sup> for pure wastewater. Xie (2011) used an average of  $1 \times 10^7$  J/m<sup>3</sup>, and estimated that it is theoretically possible to recover up to 5 times more energy in municipal wastewater than the

quantity needed to treat it. However, this estimate assumes 100% energy recovery, which is probably unlikely. At the same time, new developments are allowing wastewater to be treated more energy efficiently.

Could energy production be applied to industrial wastewaters associated with explosives production? Cyplick et al. (2012) describe an explosives production wastewater with a COD of 1,200 mg/L. Heidrich et al. (2011) studied the use of COD to estimate the energy density of wastewater. They found that different wastewater sources have different energy to COD relationships. Therefore, a simple relationship with COD can be misleading. One of their wastewaters was from a plant that processed a mix of domestic and industrial wastewater; they found an energy content of 28.7 (+/- 5.6) kJ/g COD, which would give an energy density of 34.4 kJ/L or  $3.4 \times 10^7$  J/m<sup>3</sup> — about double that of domestic wastewater. As explosives are very energy intensive compounds, it is likely that this estimate is conservative, and that higher energy densities are possible.

### **Energy Conservation in Wastewater Treatment**

Reducing energy requirements for wastewater treatment is the first step in developing energy neutral or energy producing wastewater treatment. Although this topic could easily cover an entire book or report, a condensed discussion is given herein.

#### *Energy Use at Wastewater Treatment Plants*

Table 1 is an estimate of energy usage for a 30 mgd activated sludge treatment plant. The greatest energy use is in the aeration of the activated sludge process followed by pumping. Two other larger uses are flotation thickening and transportation costs for the disposal of the sludge. Anaerobic sludge digestion also requires substantial energy input. This analysis assumes that the produced biogas is captured and beneficially used as an energy source, but in many cases, the biogas is simply flared. The biogas production was not enough to offset other energy uses in the wastewater treatment in this example. Consequently, to reach net zero or produce energy, either more efficient energy production is needed, net energy inputs must be reduced, or — most likely — both must occur.

**Table 1. Energy Estimates of Wastewater Treatment Processes for a 30 mgd Activated Sludge Plant (Owen 1982).**

Process	In-Plant Energy Consumption in 10 <sup>6</sup> BTU/day (MJ/day)	Net Plant Energy in 10 <sup>6</sup> BTU/day (MJ/day)
Influent pumping	39.2 (41358)	39.2 (41358)
Preliminary treatment	3.0 (3165)	3.0 (3165)
Primary treatment	0.8 (844)	0.8 (844)
Activated sludge	110 (116,056)	110 (116,056)
Chlorination	9.0 (9495)	9.0 (9495)
Flotation thickener	14.8 (15614)	14.8 (15614)
Anaerobic digester (assuming recovery and use of biogas)	31.2 (32918)	-84.2 (-88835)
Sludge hauling	19.1 (20152)	19.1 (20.152)
Totals	227.1 (239,603)	111.7 (117,850)

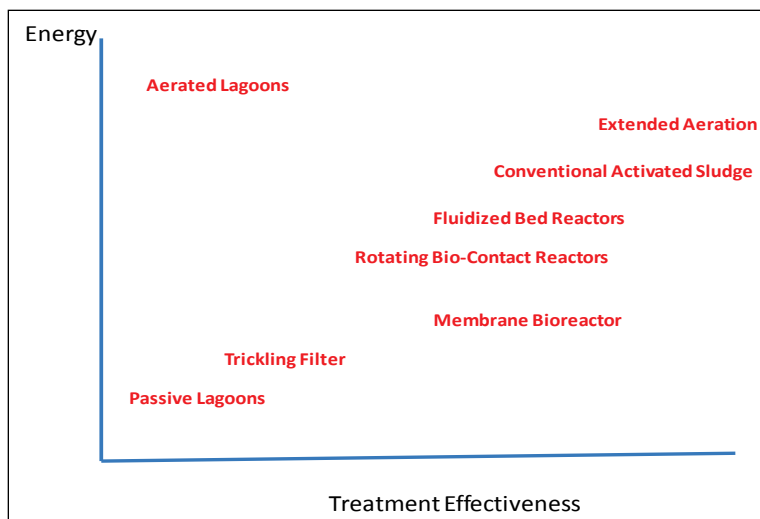
### *Energy efficient components*

A great deal of research and development has been devoted to improving the energy efficiency of wastewater treatment components. Pumping is a high energy consuming operation. Development of pumps that are more energy efficient could reduce the energy needed for pumping, and lower costs. Similarly, aeration can be a large energy consumer, but research into improved blowers and compressors as well as bubble nozzles that are more energy efficient suggests there are ways to make these operations more efficient.

### *Relative Energy Requirements for Different Treatment Options*

Different wastewater treatment approaches have different energy requirements. In general, the following pattern is seen: Aerated lagoons > Extended Aeration > Conventional activated sludge > Fluidized Bed Reactors > Rotating Bio-Contact reactors > Membrane Bioreactor > Trickling filter > Passive lagoons > Land application methods (based on Owen 1982). However, this pattern does not imply that each method provides comparable treatment. In fact, the treatment quality is essentially the reverse (with the exception of aerated lagoons, which typically do not have exceptional treatment, see Figure 2), which is why extended aeration and activated sludge are so commonly used. As seen in this pattern, suspended growth reactors tend to use more energy than fixed film approaches, and fixed film with suspended or moving beds can use more energy than those with static beds.

Figure 2. Generalized depiction of energy use versus treatment effectiveness for various wastewater treatment technologies.



Aerobic methods tend to be more energy intensive than anaerobic ones (although some anaerobic processes do require supplemental heating), particularly if the basic processes are comparable, because oxygen delivery usually requires an energy input. Anaerobic treatment can actually achieve treatment comparable or even better than aerobic ones, and it actually generates less sludge, but aerobic processes are more common because the reactions tend to be faster, and reactor sizes can be kept smaller.

#### *On-site sludge reuse*

Sludge disposal costs are a large energy consumer. On-site land application of sludge (either direct application or in a compost operation) can reduce energy needed for sludge transport while eliminating disposal costs (Medina et al. 2014a).

#### *Distributed or Satellite Treatment*

All wastewater treatment collection systems have a low point called the catchment well, in which the wastewater in a given service area is collected by gravity flow, and from there it is pumped into the wastewater treatment plant. As seen in Table 1, pumping costs are one of the highest costs for wastewater treatment. A developing approach to lower energy costs is the use of distributed wastewater treatment facilities. Distributed treatment installations reduce pumping costs because in most cases, the smaller plants can be located and built with significantly less height between the catchment basin and the plant, and the cumulative pumping energy can be kept lower (Lee et al. 2013).

As discussed in the section above, extended aeration and activated sludge are the most energy-intensive treatment approaches. These are usually required for large, centralized plants, because the volume of discharged water needs higher quality treatment in order to be incorporated into the receiving water body. Smaller, distributed plants can spread the discharge effects, and because of that, lower energy treatment options, such as membrane bioreactors or even trickling filters, could be acceptable.

Distributed systems can also reduce pipe requirements (particularly if developments are spread from each other), reducing both installation and maintenance costs (Lee et al. 2013). These systems can be used to supplement existing centralized systems (satellite systems), thereby reducing or eliminating the need for costly upgrades.

## **Stakeholders/Partners**

Potential stakeholders and partners include:

- Office of the Assistant Secretary of the Army, Installations, Energy and Environment (ASA(IE&E)) – Applications to Net Zero installations.
- U.S. Army Environmental Command (USAEC) – Potential partner for applications to installations.
- Army Maneuver Support Center of Excellence (MSCoE) (particularly Directorate of Environmental Integration) – Applications to FOBs.
- U.S. Army Sustainability Center of Excellence (SCoE) – The use of wastewater as a resource is consistent with sustainability.
- American Water (a water supply company that holds contracts for several installations) – Application to installations.
- Naval Facilities Command (NAVFAC) – Installations and expeditionary operations (United States Marine Corps, USMC).
- Air Force Civil Engineering Center (AFCEC) – Application to Air Force installations and bases.
- Net Zero Installations – The Net Zero programs do not have supplemental funding, but NZIs might have interests in energy producing modifications to their wastewater treatment processes if they are implemented inexpensively.
- Universities that have similar interests (for example, University of Illinois, University of California, Davis, Mississippi State University, Cal Poly San Luis Obispo, University of Maryland).

## **2 Energy Producing Wastewater Treatment Approaches**

Wastewater treatment can be an energy-intensive process. However, there is also inherent energy associated with the organic matter in the wastewater. As discussed above, municipal wastewater treatment is dominated by biological processes. Therefore, it is not surprising that most energy-producing wastewater treatment processes are also biologically oriented.

### **Anaerobic Digestion of Wastewater or Wastewater Sludge to Produce Biogas**

#### **Process Description**

Anaerobic digestion (AD) is a process in which organic wastes are degraded under conditions with oxygen levels too low to allow aerobic respiration. These conditions are created by limiting the influx of oxygen while providing enough organic material to consume any residual oxygen. There is a wide range of anaerobic respiration processes with the goal of most anaerobic digestion processes to produce methane ( $\text{CH}_4$ ) (Nagao et al. 2012; Viquez et al. 2008).

The methane generated is often used to power the wastewater treatment plant (WWTP) or for heating. The use of anaerobic digestion for high solids organic waste (15 to 50 percent solids; i.e., mixed organic solids such as food waste, manure, or green waste) is commonly practiced for energy recovery in Europe and the U.S.

Anaerobic digestion is a crossover technology, applicable to both solid wastes and wastewaters. Anaerobic digestion is commonly used in the U.S. for biological treatment and degradation of low solids sewage sludge (under 15 percent solids) as well as for degrading municipal, commercial, or agricultural feedstocks (Goldstein 2000). The goal of AD treatment is volume/mass reduction and stabilization (via reduction of volatile content).

#### **Anaerobic Sludge Digestion**

Anaerobic sludge digestion is commonly applied as a sludge management technology in the wastewater industry. The main purpose is to degrade the

bulk of the volatile portions of the sludge, which reduces bulk while making the sludge less offensive in terms of odors. After digestion, the sludge can be safely landfilled, directly land applied, or incorporated into a composting operation. Because the goal of sludge digestion is primarily sludge treatment, many sludge digesters do not have gas recovery as part of their systems. Without gas recovery, these systems then become greenhouse gas sources. That, combined with the potential of odors caused by sulfides and other constituents, and slower treatment, has led to many units being closed down and replaced by aerobic sludge digestion. For example, during a 2012 visit to Ft. Polk, American Water, which operates two wastewater treatment plants that served the installation, replaced one of the anaerobic sludge digestion units with an aerobic system and planned to replace the second one. A study of wastewater treatment plants at Army installations conducted by Rik Scholze (the study has not been released to date) indicated that few anaerobic digesters remained in service, and that those that still existed were not well maintained.

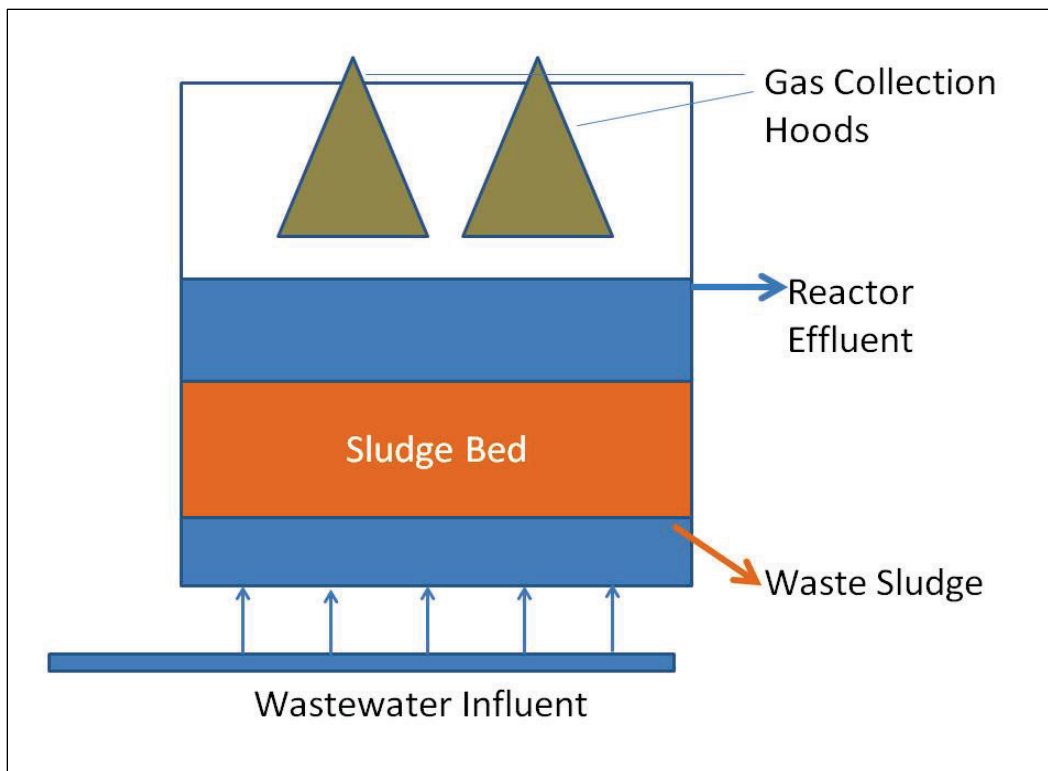
It is possible to recover energy from wastewater sludge digestion, and that could be exploited by installations that maintain their own wastewater treatment facilities. In most cases, gas production can be high enough to partially (or completely in ideal situations) offset the other energy costs from operating the wastewater treatment plant.

### **Direct Methane Generation from Wastewater Treatment**

For the direct application to wastewater, the most common approach is upflow anaerobic sludge blanket (UASB) filtration (Abbasi and Abbasi 2012, Bal and Dhagat 2001, Gomez 2011, Lettinga 1995). In these systems, a blanket of granular sludge is maintained suspended in the tank (Figure 3 is an idealized schematic). Wastewater flows upward through the sludge blanket, where it is degraded by anaerobic bacteria, including methanogens. During the flow through the blanket, the organic content undergoes biodegradation, effectively treating the wastewater. In addition, methane-containing biogas is produced, which can be captured and used for energy.



Figure 3. Idealized schematic of an Upflow Anaerobic Sludge Blanket (UASB) Reactor.



UASB is considered an advanced wastewater treatment. It has several advantages:

- It can obtain excellent treatment in a smaller treatment footprint.
- It allows for several processes to be conducted simultaneously, including nutrient removal (via nitrification/denitrification) in a single reactor.
- It generates methane gas for energy usage.
- It provides sludge digestion in the water treatment reactor, reducing sludge handling footprint.

Other anaerobic wastewater treatment approaches include anaerobic suspended growth reactors, anaerobic membrane reactors, and anaerobic membrane bioreactors.

### **Application to Installations**

Both sludge digestion and UASB technologies are available and can be applied to installations. The challenge of applying either of these is strictly one of acceptance and commitment to energy production. As mentioned earlier, the trend at Army wastewater treatment facilities has been to

replace anaerobic sludge digesters. This trend would have to be reversed, which might prove difficult because of the operational difficulties associated with these digesters. It might be more practical to install UASB reactors as new wastewater treatment needs arise, whether as a replacement of an existing system or an expansion of capacity.

McCarty et al. (2011) estimated the potential energy recovery associated with anaerobic digestion. They estimated that 80% of the energy associated with the wastewater could be converted to methane gas. However, they estimated that burning the gas could only recover 30% of the energy, which would give an overall recovery efficiency of 28%. This would be on the order of an energy-neutral system – generating enough energy to offset the system operation. McCarty et al. (2011) speculated that the development of new fuel cell approaches that could use biomethane could improve the overall recovery system, perhaps by as much as 40%.

Gas production from sludge digestion could still be increased by adding high value organic wastes to the system. This could include green plant material and food wastes. Food wastes in particular have high gas production value (Medina et al. 2014b) and are produced at large quantities at Army installations. Furthermore, an effective management approach for foodwastes is needed (Medina et al. 2014a). By coupling sludge digestion with treatment of other wastes, it might be feasible to produce energy in excess of the wastewater treatment process, which can be used to offset energy within the base.

One example of how effective anaerobic digestion is was demonstrated by the East Bay Municipal Utility District (EBMUD), which services the San Francisco area in California. EBMUD has adopted an aggressive anaerobic digestion strategy for their biosolids, and incorporated food wastes (including greases and oils) and winery wastes to produce enough biogas to meet all their needs (achieving net zero energy) and to export as energy to the local grid (NACWA 2013). The total energy is on the order of 55,000 megawatt hr/year and is estimated to save EBMUD \$3 million annually in energy costs. The process is estimated with a carbon diversion of 13,300 metric tons annually. A similar but smaller scale example is provided by Essex Junction, VT, which generates methane from its biosolids and generates energy from two 30 kW micro-turbines (NACWA 2013). Waste heat from the turbines is used to heat the anaerobic sludge digesters. An annual savings of \$33,000 has been realized, as well as a carbon reduction

of 30 tons per year. A couple of other examples of aggressive anaerobic digestion include the Detroit Water and Sewage District and Gloversville-Johnson, NY (NACWA 2013).

### **Application to Contingency Bases**

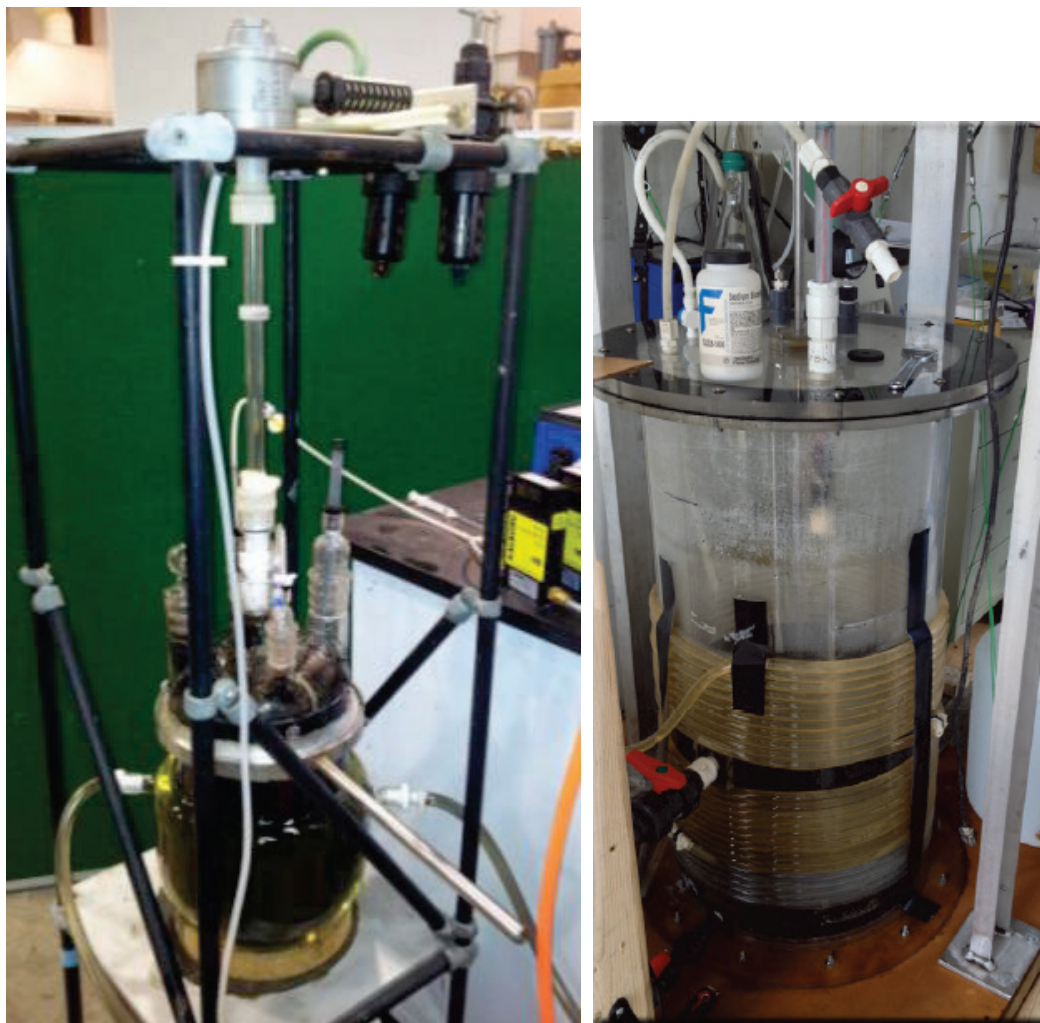
Medina et al. (2014b) conducted a study to assess the application of anaerobic digestion to wastes found at contingency bases. Studies of waste generation at FOBs were reviewed, and it was found that food waste was the second most-generated waste after wood. Furthermore, food wastes have few beneficial reuse options and can be problematic due to putrescence and vermin attraction. Anaerobic digestion was studied to assess applicability to food wastes and blackwater.

The study found that the treatment reduced the volatile solids content of food wastes by 81%, which meets USEPA standards for land application (30%, USEPA 1994). Large gas volumes were generated, and methane contents ranged from 60 to 70%. Studies with latrine wastes also had high gas production, and inhibition by toilet chemicals was minimal. A pilot study was conducted at the Contingency Base Integration and Technology Evaluation Center (CBITEC) at Ft. Leonard Wood (Figure 4 shows both laboratory and field reactors used in the study).

Calculations suggest that the generated gas could offset energy use by 15 to 30%, depending on the size of the contingency base, and fuel cost savings (fully burdened and incorporating estimates for force protection) were estimated to be as high as \$500,000 per month. Some issues were identified regarding reaction instabilities that could cause the reactors to fail. Some suggestions were identified to address these issues, particularly using a mix of wastes along with food, which should improve stability and increase the utility of the process to address waste problems in a contingency base setting.

Installing deployable waste to energy systems can be an effective approach to managing solid waste and blackwater at contingency bases (Buxton and Reed 2010). Contained reactors used for these applications allow for control of air contaminants. As energy is a critical need for base camp operation, producing energy from waste can provide a tremendous benefit for the base camps and for military operations in general.

Figure 4. Laboratory and pilot reactors used to study anaerobic digestion for treating FOB wastes (Medina et al. 2014b).



Another option — in addition to deployable reactors — would be to utilize the simple approaches adopted for sanitation and waste management in Asia and South America (Lansing et al. 2007, Lansing et al. 2008a, 2008b, Lansing et al. 2010, Lansing and Moss 2010, Viquez et al. 2008). In addition to waste treatment, these treatments generate biogas that is usable for heating and cooking purposes and electrical generation. One option is a covered lagoon system, which is a low maintenance system commonly used for agricultural operations (Figure 5). Covered lagoons are inexpensive to construct and low maintenance and could be adapted for medium to small FOBs. Another inexpensive option is the plug flow bag approach, commonly used in Asia and South America, and applicable to small FOBs. Bag reactor approaches have been developed to provide sanitation in economically challenged countries, with installation costs ranging from \$150 to \$1,500 (Lansing and Moss 2010).

Figure 5. Two examples of simple anaerobic digester reactors: covered lagoon (left) and bag reactors (right) (From Lansing and Moss 2010).



### Formation of Hydrogen Gas from Anaerobic Digestion

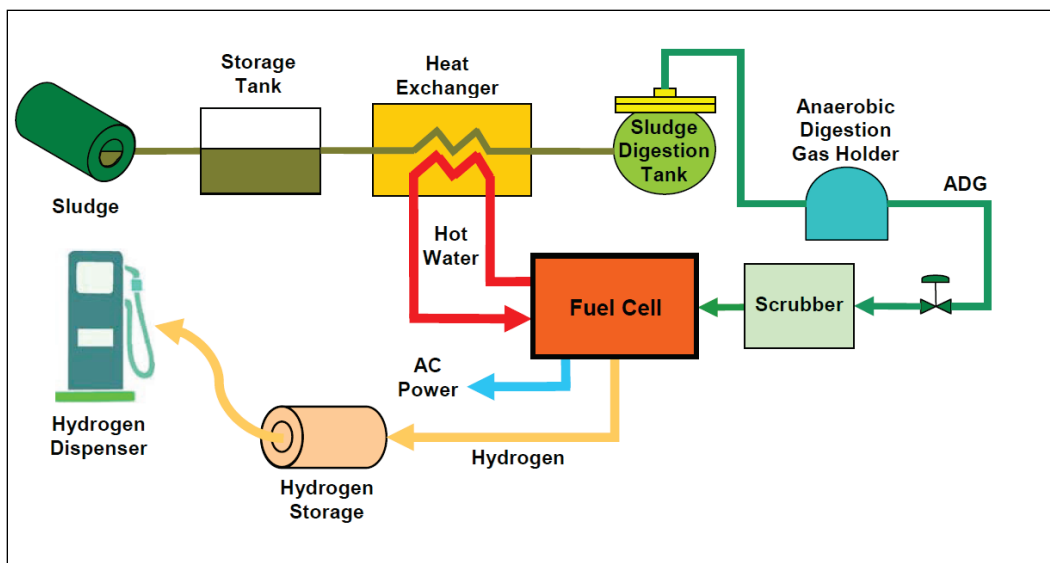
Methane is a valuable gas for energy production, but there is speculation that hydrogen gas ( $H_2$ ) could be a more useful energy resource still, as infrastructure for it is developed. Hydrogen gas has a very high energy density, which could make it a very effective fuel for vehicles. Furthermore, the primary end product of hydrogen combustion is water vapor, so it is a remarkably clean-burning fuel.

A conceptual design for a hydrogen gas-generating system from sludge digestion was developed by reforming hydrogen from methane by Perez et al. (2006), with the goal of its application at Army installations. The system was called the waste-to-energy, hydrogen production/infrastructure development and fuel cell technology (WTE- $H_2$ -FC) (Figure 6). A reformer is used to convert methane to hydrogen gas. The hydrogen gas could provide a fuel source for a conventional fuel cell, which would provide electricity and hot water. Additionally, produced hydrogen gas could also be stored and used to power vehicles for use on the installation. Several Army installations were evaluated as potential applications and Ft. Stewart (GA) was chosen as a primary candidate site. Calculations on energy production versus system modification costs indicated a potential savings of \$2.75 M over a 20-year period, as well as savings of 1.15 M kWh of electricity; 1.18 M kWh of natural gas; and 0.3 M kWh of hydrogen. However, because Ft. Stewart has a wastewater treatment system that combines flows with the local municipality, support was required from the civilian entity — but not obtained — and the project stalled.<sup>1</sup>

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<sup>1</sup> Holcomb, Frank. 2014. Personal communication with Victor Medina, September 3. Center for the Advancement of Sustainability Innovations (CASI), ERDC-CERL.

Figure 6. A conceptual design of fuel cell energy and hydrogen production from sludge digestion (from Perez et al. 2006).



## Challenges

There are technical challenges to anaerobic digestion that have hindered its widespread application. Although most can be corrected with thoughtful engineering, they do add extra complication and costs. Focused research might minimize these factors.

### Odors

One issue with anaerobic digestion is the production of odor-causing gases from the anaerobic process. These gases include hydrogen sulfide, ammonia, and mercaptans. In general, it is not possible to prevent the generation of these components. However, it is possible to regulate their release and minimize odor exposures. Nonetheless, since the process does produce fewer odors, many wastewater treatment plants are moving towards aerobic sludge digestion.

### Gas Quality

The quality of the biogas produced by anaerobic digestion depends largely on the organic material being treated and on the efficiency of the reactor. Even the best anaerobic digestion systems produce gas of lower quality than natural gas. Biogas has a methane content ranging from 50 to 70%, whereas natural gas has a methane content of 99% and higher. Biogas with methane levels as low as 50% can still be burned sustainably; however,

they do not provide as much energy potential as more concentrated gases. Low quality gas can be used for heating and cooking purposes, but it is not as effective for energy production.

Impurities can be a problem. The carbon dioxide forms the bulk of the impurities in the biogas, but constituents like hydrogen sulfide can be particularly problematic, as they can generate acids upon combustion, and the acids can cause corrosive issues in burners.

It is feasible to treat biogas to improve its quality. There are simple iron catalysts that can be used to remove hydrogen sulfide, which would allow gas to be burned more cleanly and minimize corrosive issues. Removing carbon dioxide is more involved, but can be accomplished as well. It is possible to achieve a methane content of 98%, a level comparable to natural gas. However, the extra treatments add additional cost and complication to the system.

#### *Operational Instability*

Anaerobic Digestion is a balance of two microbial types, acetogens, which begin the degradation of the organic matter; and methanogens, which take the transformed organic compounds and reduce them into methane. If this balance is disturbed, it is possible for the process to fail. In a study investigating the use of anaerobic digestion for forward operating bases, the authors found that it was necessary to take frequent samples for pH, total solids, and volatile solids to monitor reactor performance, and that frequent adjustments were needed (Medina et al. 2014b). It might be possible to derive standard operating conditions that allow for less monitoring of a predictable operation, but it appears that anaerobic digestion is a more complex system than most aerobic processes.

### **Incineration, Gasification, and Pyrolysis of Residual Solids from Wastewater Treatment**

Another option for recovering energy from wastewater is to collect the sludge, dry it, and incinerate it to generate heat and/or energy. As an organic-rich material, sewage sludge could be a high value combustion material, as the combustible fraction of dried sludge has been estimated to be on the order of 75 to 85% (Flaga 2007). The challenge is that sludge is wet and must be dried before combustion (Flaga 2007). However, drying could be accomplished by solar power in very dry climates, such as those

found in desert areas in southern California, Arizona, New Mexico, and west Texas. Waste heat from combustion, waste incineration, boiler operations, space heating, etc., could also be applied to sludge drying. A second challenge is that there needs to be an outlet for the dried sludge to be burned. This could be an existing coal power plant or coal-burning boiler operation. It could also be existing waste-to-energy incineration operations. Coal-burning cement kilns can also be an outlet. Aligning these various elements requires facilities not commonly found at military installations.

More promising is the use of gasification or pyrolysis for extracting energy from sludge. Both of these processes use high temperature in the absence of combustion to generate products that can be burned as fuel. In gasification, the reactions are performed in an oxygen-containing reaction chamber, producing a high quality methane gas similar to natural gas. Pyrolysis is performed in the absence of oxygen, and produces hydrocarbon liquids similar to diesel and JP-8. Liquid fuels are easier to store and use for most applications. However, the fuels produced by pyrolysis are not certified, which could limit their actual use. Once again, these processes require that the sludge is dried.

## **Wastewater Treatment Producing Hydrogen Gas**

Hydrogen gas is growing as an important fuel source in the United States and throughout the world (Redwood et al. 2009). Development of biological methods to produce hydrogen will be needed to meet this demand. Linking hydrogen production to wastewater treatment could be an attractive means of meeting this hydrogen demand in the future.

Production of hydrogen gas from wastewater treatment is a relatively new development with a great deal of promise for military uses, but also poses some critical challenges. Hydrogen gas is attractive since it is a high value fuel that can generate more energy per unit volume than unrefined biomethane. It can be used to power vehicles and can also support the use of fuel cells. Hydrogen can be produced by both photosynthetic micro-organisms (algae and cyanobacteria) and fermentative (anaerobic) bacteria (Logan 2004; Redwood et al. 2009). If these organisms could be cultured in domestic wastewater treatment systems and provide effective treatment, then a very effective energy production system could be developed. Azbar et al. (2009) used a dark, fermentative reactor to treat a high chemical oxygen demand (COD) wastewater derived from a cheese whey manufacturing. Concentrations of hydrogen in the gas ranged from 5 to 82, with an average



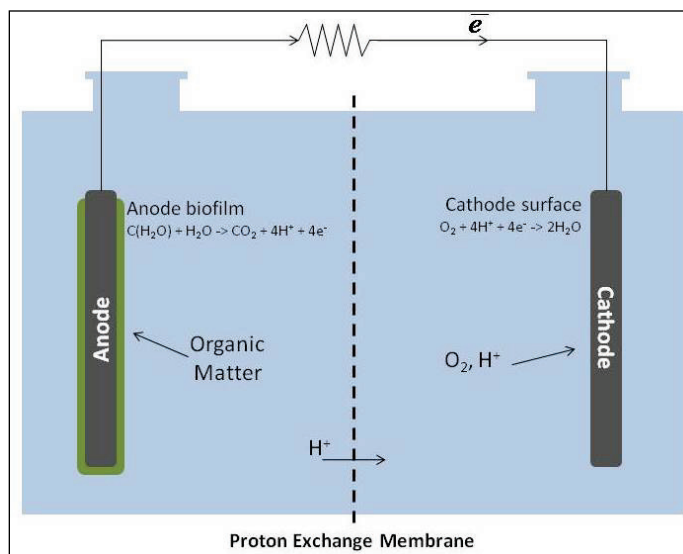
of 45%. Treatment of the organic material was inconsistent, although effective treatment was obtained during some portions of the experimental effort.

## Treatment and Energy Generation using Microbial Fuel Cells

### Microbial Fuel Cells

Microbial fuel cells (MFCs) are biological reactors that convert the chemical energy stored in organic matter to electric energy. This is done by taking advantage of the ability of certain bacteria, exoelectrogens (Logan 2008a) or electricigens (Lovley 2006), to transfer electrons to a solid state anode as a terminal electron acceptor. The resulting potential is resolved by providing a cathode for the ultimate reduction of a lower potential electron acceptor, usually oxygen. By placing a resistive load between the electrodes, the current generated by the electrode potential difference may be used to provide electrical power. Figure 7 shows a generalized schematic of an MFC with oxygen reduction at the cathode.

Figure 7. Generalized schematic of a microbial fuel cell with oxygen reduction at the cathode.



### Processes involved with MFC Reactions

The basic processes involved in the efficient generation of electrical energy in MFCs are mass transport of organic matter to exoelectrogenic bacteria; uptake and metabolism of organic matter by exoelectrogenic bacteria with charge transfer to a solid state anode; current resulting from generated potential difference across a resistance; transport of protons across the

compartment separator – usually a proton exchange membrane (PEM) – and reduction of oxygen at the cathode surface. The contributions of the individual processes to the internal resistance of the system have been reviewed by Logan et al. (2006). Different approaches have been taken to reduce mass and charge transfer resistances to the lowest practical levels and thereby increase the power output of the MFC. These include applying adaptation pressure in the form of electrical potential to the anode to select for efficient exoelectrogenic bacteria (Yi et al. 2009); evaluating the separator material (Zhang et al. 2010); redesigning cathode architecture, and utilizing electrode materials to their full advantage (Sun et al. 2010). These efforts have led to increased power densities in laboratory-scale MFC reactors. Present and future efforts will require close evaluation of the potential for scaling up effective reactor designs to reliably harvest energy (Logan 2010).

## **Resistance**

Water is, by itself, a highly resistive material in terms of electrical transmission. This changes, of course, as ions are dissolved into solution. However, the electrical resistance of water can hamper the energy recovery of an MFC. One approach for minimizing the resistance of the MFC reactor is collapsing the scale of the reactor to bring the electrode materials closer together. Reducing the scale of the electrode assembly accomplishes two tasks. It reduces the mass transport distance between the anode and cathode, minimizing internal resistance associated with mass transport of protons from the anode surface to the cathode surface. It also reduces the total volume of the MFC electrode assembly leading to higher power densities on a per volume basis. Butler and Nerenberg (2010) demonstrated the utility of layering the anode, PEM, and cathode with close spacing by constructing flat plate assemblies for acetate-fed MFCs with cathodes left open to the air. They also showed increased current efficiency in assemblies that included a polytetrafluoroethylene (PTFE) diffusive layer that reduced the flux of oxygen to the cathode surface. This was attributed to a reduction in oxygen passing through the cathode-PEM layer to the anode. This experimental system provided a useful test of closely spaced electrodes; however, to increase the volumetric density of electrode surface area, a configuration other than flat plates is advisable. Butler (2009) conducted a proof-of-concept test for using electrode materials applied to the inside and outside of a Nafion® membrane tube. By vacuum aspiration and spray coating the respective surfaces of the tube, Butler developed a functional tubular MFC. This demonstrates that no fluid chamber is required between

the anode and the PEM to facilitate proton transport to the cathode and opens the possibility of integrated MFC components based on small tubular assemblies with a high volumetric specific surface area.

### **Electrode and Membrane Materials**

The relative advantages and disadvantages of different electrode and membrane materials have been studied (Logan et al. 2006, X. Zhang et al. 2010, F. Zhang et al. 2010). Different approaches to fluid flow to allow for maximum efficiency and substrate utilization have also been tested (Lorenzo et al. 2009, Katuri and Scott 2010), and initial scale-up efforts using food processing wastewaters have been attempted (Logan 2010). It is less clear how the microbial ecology of the anode respiring community will change over time or respond to dynamic conditions and affect the performance of an MFC system in a wastewater treatment role. The requirements of the anode community will set limits on the utility of an MFC, and these limits require delineation in order to increase the probability of successful MFC application. Two major questions are the effects of competing electron acceptors in the wastewater stream and the effect of hydrodynamic conditions on the viability of the exoelectrogenic community. Some competing acceptors, including residual oxygen and nitrate, may be expected to be present in the wastewater feed at some level. These acceptors will provide an opportunity for nonexoelectrogenic bacteria to become established within the anode compartment, diverting electrons resulting from the oxidation of organic matter away from the anode and lowering current efficiency. In a deployable treatment system where the goal is energy neutrality for wastewater treatment, some loss of efficiency may not prevent the successful harvesting of enough energy. At some point, though, it may be expected that enough competing acceptor is present to outcompete the exoelectrogenic bacteria and prevent the establishment of an electrical potential. The dynamics of this process will need to be understood as scale-up is considered. The hydrodynamic management of an exoelectrogenic biofilm will also need to be considered before scale-up can be completed. Hydrodynamic forces within the anode chamber will affect substrate mass transfer and biofilm morphology in the system. These, in turn, may affect the overall biofilm ecology and the viability of exoelectrogens in the anode compartment.

### **Passive Filtration Membranes**

Recent advances in membrane manufacturing have helped produce low-pressure, high-flux microfilters and ultrafilters. Such membranes can be operated at a low positive or negative pressure (0.1-0.3 bar, equivalent to 1-3 meters of submersion in water), yielding a permeate flux in the range of 15-50 L hr<sup>-1</sup> m<sup>-2</sup>. An ultrafilter has a membrane pore size smaller than 0.1 µm and is effective in rejecting large organic molecules and a wide range of microorganisms, including viruses. The effluent water quality after ultrafiltration typically has <1 mg L<sup>-1</sup> of total suspended solids (TSS) and <0.2 NTU of turbidity, with additional removal of BOD.

Polyvinylidene fluoride (PVDF) has excellent physical strength, is inert to a wide range of chemicals and can be bundled in the form of flexible hollow fibers or disks that are loosely suspended in water. Such flexible configurations do not require external physical support and have been successfully applied in modern membrane bioreactors (Judd 2011).

### **Electrical Production**

To date, laboratory studies of MFCs have had very limited energy recovery, on the order of 1% of the potential energy in the system (Xie 2011). Furthermore, most research studies to date have used synthetic wastewaters with high energy and easy to degrade constituents like sucrose and glucose. However, it is at least theoretically possible for these systems to have recoveries close to the level of anaerobic digestion. And since the systems directly generate energy, there are no losses associated with combustion. Ultimately, MFCs may turn out to be more efficient at generating energy than anaerobic digesters.

Like most biological processes, MFC substrate utilization is linked to the concentration of the organic matter in the solution. Since substrate utilization corresponds to electrical production, there can be a drop off in electrical production as the organic matter is degraded. This means that MFCs generally produce more energy in concentrated solutions.

### **Treatment of Municipal Wastewater**

First, in terms of energy output, Cheng et al. (2006) studied MFC treatment using 500 mg L<sup>-1</sup> glucose solution as a substrate. A maximum power density of 1540 mW m<sup>-2</sup> (51 W m<sup>-3</sup>, CE = 60%) was obtained (1 watt = 1 J sec<sup>-1</sup>). The same system was then applied to a domestic wastewater with a chemical

oxygen demand of 255 mg L<sup>-1</sup>. The maximum power density was reduced to 464 mW m<sup>-2</sup> (15.5 W m<sup>-3</sup>, CE = 27%). Thus, potential energy production from wastewater treatment appears to be on the order of about 1/3 of that from glucose. Liu et al. (2004) found modest, but sustainable energy production (26 mW m<sup>-2</sup> maximum) during treatment of domestic wastewater, while removing 80% of the wastewater COD.

In another study focusing on municipal wastewater, Ahn and Logan (2010) found that highest energy production came in a continuous flow reactor operated at mesophilic conditions, giving a maximum power density of 422 mW m<sup>-2</sup> (12.8 W m<sup>-3</sup>). At these conditions, COD removal was 25.8%. For comparison, in Hammer (1986), the biological portion (after sedimentation) of typical wastewater treatment system was shown to remove about 76% of biological oxygen demand (BOD). However, BOD generally describes the more easily biodegradable portion of organic matter. If we assume that BOD in domestic wastewater is about 60% of COD, then the COD removal would be about 46%. Consequently, the results from Ahn and Logan (2010) do not quite meet treatment standards, but are in the general order of magnitude needed for successful treatment.

As MFCs are generally designed to generate energy, it is not surprising that they are not quite as efficient at actually treating wastewater. Since the treatment must occur at the biological electrode, there are limitations based on the electrode surface area. In addition, the depth of the biological growth on the electrode is limited because of the need to promote electron flow. The results from the Ahn and Logan study are promising nonetheless, and — if improvements can be made — MFC treatment could approach that of other wastewater treatment reactors.

### **Issues with MFCs**

MFCs are a promising technology for energy production via treatment of wastewater. It is the only technology in which electricity can be directly obtained from the treatment process, as the other approaches require the burning of gas or the processing of biomass to recover energy. However, to date, the vast majority of MFC work has been done at the bench scale, with a few pilot-scale applications (Xie 2011; Logan 2010). Another issue is the associated costs. The electrode and membranes are generally expensive (Lucentini 2006), and it has been estimated that an MFC would be hundreds of times more expensive than a similarly sized anaerobic digestion unit. However, with the relatively high investment being made in

this technology, it seems that these issues will likely be resolved within the next 5 or 10 years. The next section discusses a new study that shows particular promise in moving MFC application forward.

### **Anaerobic Electrochemical Membrane Bioreactor (AnEMBR)**

A new development in direct energy production is described by Katuri et al. (2014), which described an approach called the Anaerobic Electrochemical Membrane Bioreactor, or AnEMBR. The process combined a microbial electrolytic cell with a membrane filtration system based on a porous, electrically conductive, nickel-based hollow fiber material. The process combined biodegradation and membrane filtration to achieve high quality effluent (>95 COD reduction). And by concentrating the organic content at the membrane, higher levels of electrical production are possible as well: up to 71% recovery of the energy in the substrate, primarily as hydrogen gas. Results are very promising, but the system so far has only been developed and tested at bench scale.

## **Wastewater Treatment-Producing Materials Suitable for Biofuel Production**

### **Biofuels**

Biofuels are rapidly developing into a large industry in the United States (Fulton et al. 2014). Currently, the Army and other DoD organizations do not directly use biofuels, but there are several programs with the goals of developing, evaluating, and certifying biofuels for military vehicles.

### **Microbial Feedstocks for Biofuels**

Certain species of algae (Sawayama et al. 1999) contain oils and fatty acids/alcohols/esters that could be extracted and used for biofuel production (Ning and Liu 2014). Researchers are also investigating the use of genetic engineering to develop bacteria like *Escherichia coli*, with desirable oils and fatty acids/alcohols/esters that can be harvested for biofuels (Howard et al. 2013, Khosla 2006).

### **Wastewater Culturing of Microbial Feedstocks**

The concept of growing microorganisms and harvesting them to make fuels is very exciting from the standpoint of developing a fossil fuel-free means of energy. However, to grow enough microorganisms to derive fuel

requires large reactors and significant food sources to promote their growth (Medina et al. 2003, Sawayama et al. 1999). Wastewater treatment facilities offer both size and food sources. Furthermore, growing biofuel-producing organisms in wastewater reactors has no impact on food production, unlike biofuels developed from plants such as corn. If biofuel-producing organisms could also provide effective wastewater treatment, and if these could be concentrated in the resultant sludge, then a sustainable process could be created.

### **Treatment of Wastewater with Biofuel Producing Organisms**

Algae, which have been the primary focus of microbial biofuel to date, can be used to treat wastewater (Pittman et al. 2011). Solar lagoons are an established wastewater treatment technology. The concept is that algae uptake nutrients and release oxygen, stimulating biological activity to degrade organic compounds. These approaches can work, but are usually limited to areas with relatively low flows and with large space. Although these can be applied to municipal wastewater, the main focus of these reactors tends to be for nutrient removal.

Lundquist (undated) presented a study on using algae in large ponds to generate a biodiesel stock. The study showed that algae can be very effective at nutrient removal in carbon-limited wastewater, and found 30% lipid content in the algae, which could be refined into biofuel. Algae ponds commonly have relatively low algal productivity, but new approaches, such as paddle wheel mixed, high rate algal ponds, can double algal productivity (Craggs et al. 2011, Park et al. 2011). In addition to potential biofuel production, the process can sequester carbon dioxide. Lundquist et al. (2010) also explored the concept of coupling algal biofuel with wastewater treatment. However, both the Craggs and Lundquist studies are only hypothetical. Algae cannot be applied in conventional wastewater treatment. However, genetically modified bacteria have potential for this application. Studies have been conducted with *E. coli*, and have shown promise, but implementing the bacteria in a full-scale system appears to be years away.

### **Issues**

Developing biofuels from algae is still a developing process. A report from the 2014 Algal Biofuel Workshop hosted by the U.S. Department of Energy (DOE) indicates that converting algae into usable biofuel is a very complex process (ITECS 2014). Selection of appropriate algae whose oils can be

extracted and refined is complicated and challenging and tying this process into those microorganisms which also provide useful wastewater treatment further challenges the process. At the present time, it appears that a commercial biofuel-producing wastewater treatment process is still years away. Algal systems in particular have limitations in terms of depth and light penetration, which can result in very large surface areas (Medina et al. 2003).

Even if a biofuel-producing reactor was available, a biofuel stock production strategy would have to be developed. This would require integration with a private entity to take the microbial feed stock and produce the fuel. And if such an entity were to discontinue biofuel production, the wastewater plant would lose energy production. Therefore, it seems that a biofuel-producing wastewater treatment approach would not be an easy-to-implement strategy for military installations.



### **3 Resource Recovery with Wastewater Treatment**

Energy is just one resource found in wastewaters. Wastewaters also contain chemical and biological constituents that could be recovered as industrial feedstocks. The concept of resource recovery from wastewater is relatively new, but is being rapidly developed. The main focus is extracting nutrients from wastewater, although more advanced research is exploring the recovery of polymers that can be used to produce bio-plastics and recover high value metals. Westerhoff et al. (2015) estimated that the value of metals in a typical wastewater sludge to be \$280/ton, and that such metals from sludge generated from a community of one million would be valued at \$13 million annually.

#### **Nutrient recovery**

N and P are life-essential macronutrients that are extensively used for agricultural purposes. At the present time, the synthetic nitrogen and phosphorous fertilizers that are used for food production are produced through energy-intensive processes that use nonrenewable resources (e.g., natural gas and phosphate rock).

Since nutrients in domestic wastewater represent a renewable resource, recovery of these nutrients into a usable form from waste streams has emerged as a key component of sustainable approaches to managing global and regional nutrient use. Research has shown that recovery of resources (e.g., water, energy, nutrients) from wastewaters has the potential to reduce energy consumption and improve treatment efficiency for municipal WWTPs.

The shift to embrace nutrient recovery embraces the “fit-for-purpose” concept, whereby all resources in water are harvested to meet current and future demands of our growing society. It also fits within the larger concept of integrated nutrient management approaches that emphasize reuse and can allow utilities to become resource recovery plants. Nutrients can be recovered in liquid streams, biosolids, or as chemical nutrient products.

## Liquid Streams

The simplest method of recovering nutrients from wastewater is to apply the wastewater directly as a water and nutrient source for agricultural activities. This process has a very long history, and is still widely practiced throughout the world. Although application of municipal wastewater for agriculture is not used in any form in the United States, applications could serve to promote sustainability operations in contingency operations, as specified in Unified Land Operations (USDOA 2011).

The simplest method is simply to divert wastewater flows and directly apply them to agricultural fields. A second process is to provide conventional biological treatment, then apply the effluent as an agricultural amendment. A third approach involves conventional biological treatment followed by disinfection, then application as an agricultural amendment.

Application of untreated municipal wastewater is not considered a sanitary technology, but it is still widely practiced in many countries throughout the world. A modified version of this might have utility in managing wastes from FOBs. In the documentary *Camp Leatherneck*, which documented activities at a large FOB in Afghanistan in the height of Operation Enduring Freedom (National Geographic 2010), the wastewater flow from the camp was captured by Afghan farmers, who used it to support a very successful agricultural operation. Although there were concerns that this could lead to propagation of disease by contact with the wastewater, the process could be modified by a simple disinfection system, which would address this issue. In a similar manner, Mexico City, which is the largest city in the Western Hemisphere, disposes of about 75% of its wastewater (untreated or partially treated) by selling it for irrigation for surrounding agriculture (Downs et al. 1999). The treated sewage reportedly improves yields on the order of 25 to nearly 35%, compared to other areas receiving traditional irrigation. The operation is massive, covering an area as large as the state of Rhode Island. The irrigation is used on crops (mostly alfalfa) that are used for animal feed, reducing the threat of trophic transfer. However, there are concerns that decades of this practice has resulted in degradation of the local groundwater aquifers with organic material and pathogenic microorganisms (Downs et al. 1999).

With the development of deployable wastewater systems (Waisner and Medina 2012), this type of nutrient recovery might also be useful for contingency applications, albeit on a much smaller scale. The greatest

concern with using liquid municipal wastewater as a nutrient source is the promotion of pathogenic microorganisms, either by direct contact with the wastewater or by uptake into foods. However, there are means to address this issue. First, conventional biological wastewater treatment approaches can greatly reduce pathogenic microorganisms, and these alone may be sufficient to allow for beneficial agricultural use. Disinfection approaches can also be used, including chlorination, ozonation, and ultraviolet. Disinfection can be applied directly to untreated sewage or to biological residuals. Disinfection of wastewater can be challenging, as the high organic content can make complete disinfection very difficult to attain. In addition, in the case of chlorination (which is probably the most available method worldwide), disinfection of high organic wastewater can promote the formation of undesirable products such as trihalomethanes. Solar energy can be an inexpensive means of providing pathogenic deactivation. The wastewater (raw or treated) can be diverted into a shallow basin to allow ultraviolet penetration from the sun to kill pathogenic organisms. This approach is simple and low cost, but it does require substantial land, can itself be a source of odors or disease, and may be overrun by algal growth. Pathogenic transfer can be reduced by further using the wastewater to irrigate crops that are used to feed animals, as opposed to using it directly for human consumption.

### **Biosolids derived from sludge**

Sludges are generated as a by-product of conventional wastewater treatment processes (see Figure 1). Sludge consists largely of waste microbial biomass generated from the digestion of organic wastes. Microorganisms accumulate carbon, N, P, and other micronutrients in their structures; these all have value as nutrients.

Sludge undergoes a series of treatment processes to decrease its volume, including digestion to degrade additional volatiles' organic content and dewatering. Digestion can be aerobic or anaerobic. While there are several means of dewatering, including passive and active gravimetric methods, solar evaporation of excess water, screw press, chemical processes, and centrifugation.

Following digestion and dewatering, sludge can be safely disposed of in a landfill. However, most sludge in this state can also be beneficially applied to soils as a soil amendment. In order to be applied to soils, sludges must meet two EPA criteria. First, volatile solids of the sludges must be reduced

by 30%; second, the sludge must have metals concentrations below certain threshold criteria.

If the sludge meets the criteria for land application, then it may benefit soils in two ways. First, the organic content can improve water-holding capacity of the soil while stabilizing nutrients and contaminants. Organically amended soil tends to increase particle adhesion, improving erosion resistance. Sludges also add nutrients to the soil; therefore, they act as fertilizer to soils.

There are two ways in which digested and dewatered sludge can be applied to soils. First, it can be directly applied to soils. Since even dewatered sludge is very wet (its solids content is on the order of 25 to 40%), it still can contain a significant volatile fraction, making it nevertheless quite putrescent. Dewatered sludge needs to be applied rather quickly and is often plowed or disked into soils.

Incorporating sludge into compost provides additional treatment that makes it much more stable. The excess water in the sludge can be partially consumed by evaporation by the heat and biological processes found in the composting process, while the rest can absorb into the structure of the compost. Compost is an excellent soil amendment and it can be stored nearly indefinitely and — if properly prepared — has minimal odor issues.

Liquid wastewater, directly applied sludge, and compost can be beneficial soil amendments. That said, the municipal wastewater process of mixing urinic, fecal, and other liquid wastes tends to concentrate carbon at the expense of N, P, and other nutrients. Consequently, these natural products do not have the same nutrient density as petrochemically prepared or mined fertilizers. Therefore, sewage-derived fertilizers often do not meet the needs of high-volume agricultural operations and demand for these products is limited in some cases.

## **High Value Chemical Nutrient Products**

In order to produce nutrient products for high value agriculture (as well as other industries, like disinfectants and munitions), nutrients must be concentrated beyond what are found in the use of liquid wastewater or even biosolids. Two methods are available: extractive approaches to remove these from municipal or industrial wastewater streams, or source

separation, to focus on recovery from the wastewater sources where these nutrients are most concentrated.

### **Extractive Approaches**

Extractive nutrient recovery is a strategy for concentrating nutrients for beneficial recovery during wastewater treatment. In this option, energy and resources are used to accumulate and produce a nutrient product that has value in a secondary market. Resale of this product will ideally offset operating costs as well as potentially provide a profit.

Nutrient concentration in influent to wastewater treatment plants generally ranges from 10 to 50 mg N/L and from 1 to 10 mg P/L. As the nutrients progress through treatment steps, they can be removed in a gaseous form (N), accumulate in the solids (both N and P), or be discharged in the liquid effluent (both N and P). Extractive nutrient recovery is most effective when nutrient concentrations are above 1000 mg N/L and 100 mg P/L and when flows are relatively low. Consequently, resource extraction appears to be best suited for sludge treatment processes (Parker et al. 2009). Alternatively, membrane treatment approaches can be to concentrate the wastestream to make resource recovery more efficient (Verstaete et al. 2009). There is a need to develop multiple strategies to work with different concentrations and forms of nutrients throughout the plant. The drive to reduce water in wastewater may further help create increased opportunities in resource recovery.

The use of extractive nutrient recovery to help manage the nutrient content of domestic wastewater can be facilitated if it is performed in a three-step framework:

1. Accumulation of nutrients to high concentrations
2. Release of nutrients to a small liquid flow with low organic matter and solids content
3. Extraction and recovery of nutrients as a chemical nutrient product

Extraction can be accomplished using biological (N and P), physical (N and P), and chemical (mainly P) techniques. Biological (N and P), physical (N and P), thermal and chemical methods (primarily P). Multiple options for each stage of treatment can be developed and optimized separately, allowing the most appropriate solution to be selected.

### *Biological Extraction*

Biological accumulation techniques center on microbial accumulation in which specially adapted microorganisms are able to uptake (N and P) and store nutrients. Plants such as duckweed can also be used as part of passive nutrient accumulation/treatment strategies.

Biological systems can remove between 70 and 90% of N and P from waste streams and are effective for treating a wide range of nutrient concentrations, including the dilute content of nutrients typically associated with typical municipal flows. Key requirements for using biological accumulation processes are an effective solid-liquid separation process like clarification or membranes to allow recovery of the nutrient-rich biomass, as well as an appropriate release technology for subsequent processing.

### *Chemical Extraction*

Chemical extraction is another means to recovering nutrients from wastewater. There are several approaches available. Metal salt addition is a potential approach that can be used to help accumulate nutrients (mostly P). During this process, the metal salt reacts with soluble P to form an insoluble phosphate complex, which is solid and can then be physically separated from the waste stream. Aluminum and iron solutions are often used for this purpose and can achieve greater than 85% P removal from the dilute stream, with the chemical solids being separated during filtration or clarification.

### *Physical Removal*

Another strategy that can be used to accumulate nutrients from the mainstream flow is adsorption and/or ion exchange (Parker 2009). These processes can be used to remove N and P from dilute waste streams, with removal efficiencies ranging between 50 to 90%. In this approach, a sorbent or ion exchange material is packed into a column. As the wastewater flows through the column, N or P is either sorbed or chemically attracted to specific sites on the material. This approach has been used at pilot and full-scale tertiary filtration applications to help remove phosphorous. One of the biggest challenges with using these options is the regeneration step, which requires use of costly chemical brines and the need for replacement of spent adsorption media. Therefore, it may not be economically feasible to implement adsorption and/or ion exchange at larger plants. However, there

are new research developments that might make this option more affordable in the future. For example, laboratory-scale research is investigating the use bioregeneration as a method to help reduce costs associated with regeneration and replacement of sorbent material.

Electrodialysis is a physical extraction technology that allows recovery of all ions from nutrient streams at nutrient concentrations below 2000 mg/L, and is a highly promising technology to the extractive nutrient recovery field. In this process, an electrical current is used to separate anion and cations across an ion exchange membrane. This technology has been evaluated at laboratory-scale for resource extraction, but it does show potential implementability at full scale and has been used for industrial and groundwater treatment (Strathmann 2010).

#### *Thermal Recovery of Nutrients*

Thermochemical options can include wet oxidation, incineration, gasification or pyrolysis. In these processes, high temperature is used to destroy organic material and produce a solid product containing P, which can then be chemically released. Nitrogen is usually lost through gaseous emissions during these processes. Chemical release of nutrients from the char, ash, biosolids, or undigested sludge can then be accomplished using concentrated acids or bases at temperatures between 100 to 200 degrees C. The liquid stream is then subjected to extraction technologies to recover the nutrients.

#### *Vapor Phase Recovery of Nitrogen Products*

To recover N-only products, liquid gas stripping of ammonia can be used (Quan et al. 2009). While commercial technologies exist and are technically feasible, ultimate implementation of this process will be dependent on the cost for products that will be recovered. While this process is established in industrial applications, it has not been extensively applied for recovery of N from municipal wastewater.

#### *Processing Nutrients Extracted from Wastewater*

Once accumulated, the nutrients within the biomass or chemical sludge/slurry must either be released and then extracted to a chemical nutrient product or directly extracted to obtain a chemical nutrient product. Release technologies allow us to recover the nutrients into a

low-flow high-nutrient content stream with minimal solids content, which can be used for extraction processes. Release technologies typically employ some combination of biological, thermal, chemical, or physical processes.

Currently, commercial technologies for extractive nutrient recovery primarily produce chemical nutrient products that are used in agricultural applications. This is because 85% of all nutrient products are associated with agronomy. As food demand is expected to rise with an increasing global population, it is expected that demand for chemical nutrient products will follow. This represents an opportunity for the wastewater treatment market to develop niche products that can be used in this field.

#### *Concentration of Extracted and Recovered Nutrients*

The next step of the extractive nutrient recovery process is the extraction and recovery of chemical nutrient products from the concentrated liquid streams. These extraction processes can be inserted downstream of accumulation or release technologies. At present, each extraction technology requires pretreatment to reduce the solids content and/or change the temperature or pH of the liquid stream to a suitable condition for the extraction technology. One example of a commonly applied extraction technology is chemical crystallization. In this process, the soluble nutrient is precipitated and recovered as crystalline products. Products that can be generated by the process include struvite (magnesium ammonium phosphate) and calcium phosphate (hydroxyapatite, P only). In the case of struvite formation, the pH and concentration of magnesium phosphate, an ammonium, is controlled to allow the precipitation of the chemical nutrient product, which is then separated from the liquid stream via gravity or mechanical separation. Further drying and processing of the product is also commonly performed. Multiple variations of this chemical crystallization process have been commercialized. Up to 90% removal efficiencies for P and ammonia removals up to 30% can be expected if struvite is the product of choice.

#### *Assessment of Extractive Technologies*

Extractive technologies have been tested in the laboratory and in limited pilot settings. Full-scale applications are quite limited. The economics of extraction must compete with the costs of mining nutrients or producing them from petrochemical sources. WERF (2011) found that extraction was generally not cost competitive.



## Source Separation

As seen from the sections above, it is possible to extract nutrients from wastewater. However, these require chemical, biological, or energy impacts. Separating wastewater sources can enhance resource recovery from wastewater without the need for extraction from the wastewater or biosolids, and can also result in smaller, more efficient wastewater treatment plants for the remainder of the municipal wastewater. The rationale for urine source separation is presented in Maurer et al. (2003), and in Larsen et al. (2007). Humans produce about 1.4 L of urine and 140 g of feces per person per day. Urine contributes 81% of the N and 50% of the P in pure domestic wastewater. N and P can both cause eutrophication and may be removed in biological wastewater treatment plants (Maurer et al. 2003, Larsen et al. 2007). The excess nitrogen results in treatment plants being built several times larger than they need to be compared to the size that would be required with urine removal.

Wastewater source separation has a long history (Larsen et al. 2009). Rural areas throughout the world have practiced this to produce crude fertilizers, homemade disinfectants, gunpowder, and other basic products. Urine separation has also been used in times of war to produce nitro-compounds for the production of propellants and explosives, including the Civil War (primarily by the Confederacy), World War I (by both Great Britain and Germany), and World War II (primarily by Japan). So source separation has generally been a low technology approach for relatively undeveloped rural communities or a strategy of desperation during war. However, the concept has developed some interest in this as a potential approach for large-scale municipal wastewater operations.

An interdisciplinary project called Novaquatis was conducted by the Swiss Federal Institute from 2000 to 2006, focusing on urine source separation technology (see [http://www.novaquatis.eawag.ch/index\\_EN](http://www.novaquatis.eawag.ch/index_EN), Larsen et al. 2009). Modern urine-separating toilets (NoMix) were installed and evaluated (see [http://www.roevac.com/page/en/page\\_ID/54?PHPSESSID=6a298fabb9e2edc5f8456e01e08dcc5c](http://www.roevac.com/page/en/page_ID/54?PHPSESSID=6a298fabb9e2edc5f8456e01e08dcc5c)). Other studies were conducted in Sweden (Hellstrom and Johansson 1999).

These projects found that the toilets were positively accepted by the users. However, the demographics tested (the highly environmentally conscious Swiss and Swedes) might not be a good comparison to an American military population. The toilets are different and may not be comfortable for most American soldiers. The toilets efficiently separated the urine

waste from other wastes, allowing for efficient recovery of the nutrients. Other source separation studies have been reported in Europe, but none have been conducted in the United States (Parker 2009).

Upon separation of urine at the source, two nutrient management approaches exist: on-site urine treatment or transport to a centralized plant. On-site treatment was found to be more practicable (Larsen et al. 2009), primarily due to the extra piping required for centralized treatment. Two problems are associated with the conveyance of urinic wastes: blockage of urine-conducting pipes due to biological hydrolysis of urea with subsequent precipitation of P compounds, which can block pipe flows. However, localized collection may not be practical for military facilities.

Processing methods described in the previous section can be used to concentrate and process the urinic water. However, because the nutrients are concentrated in a small volume of liquid, the processes can be more efficiently and economically applied. Zhang et al. (2014) explored forward osmosis as a means for efficiently separating nutrients from source-separated urine.

One criticism is that there are no economies of scale for decentralized systems as they are usually only considered where it is too expensive to build sewers. Larsen et al. (2007) suggested that with appropriate quantities and price drops in membranes, a break-even compared with conventional technology is achieved at \$260 to \$440 U.S. per person, although they see a critical research need in the area of maintenance.

### **Environmental benefits of enhanced nutrient recovery**

Nutrients are a major contaminant in some areas, promoting algal growth and lower oxygen levels. Enhanced nutrient recovery can remove these nutrients from the wastewater stream, reducing the potential of eutrophication.

### **Wastewater-derived nutrients**

Chemical nutrient products destined for agricultural purposes must meet some minimum requirements. For example, all products must have consistent nutrient content and possess no/minimal odors. Solid products must have uniform size, comprise no less than 95% total solids, have less than 1% dust content, and have a minimum bulk density of at least

45 pounds per cubic foot. Furthermore, chemical nutrient products resulting from extractive nutrient recovery processes have negligible pathogen or trace organic contaminant concentrations. This is an additional benefit over biosolids for these products. Moss et al. (2013) recommend marketing efforts within niche markets to maximize resale, as competition with existing supply chains will be difficult.

Market analysis indicates that products with P only or N and P have a higher resale value than products comprised of N only. This may be related to the high demand for easily minable phosphate rock, which can drive up fertilizer cost.

Although there appears to be a general consensus that nutrient recovery can benefit the industry, technical, social, and economic challenges remain (Guest et al. 2009). Many of these barriers stem from a lack of technical and economic knowledge. A systematic evaluation of treatment efficiencies, costs, energy balances, and recovered product yields is needed. To date, collective experience has shown that successful implementation of extractive nutrient recovery systems is highly dependent on the amount of nutrients that must be removed or recovered and that payback periods are shorter for more concentrated waste streams. Accordingly, direct extraction of nutrients from mainstream flows is not technically or economically feasible. Instead, the three-step framework is more appropriate, whereby nutrients are first accumulated, released, and then extracted.

## Plastics

One of the most nontraditional technologies under development is the production of a biodegradable plastic using polymers isolated from biosolids. One such material includes polyhydroxyalkanoates (PHAs), which can be used to produce thermoplastics (Parker 2009, WERF 2011). Micromidas Inc. (<http://www.micromidas.com/>) is developing a biological process that will use the carbon and other nutrients in biosolids to generate small particles of biodegradable plastic, similar to the process that uses glucose or fructose to make biodegradable plastics (Spivack 2011). The resulting plastic will have a lifespan of months, instead of the centuries currently required to breakdown petroleum-based plastics.

## Metals

Metals can also be potentially mined from wastewater (WERF 2011). Silver and cadmium are increasingly found in wastewater, and these are expensive enough to potentially warrant recovery. Nanosilver, for example, is used in sunscreen, deodorants, and in odor-resistant clothing. Zeolitic sieves can be used to recover specific metals, and electrical methods, such as electrokinetics or electrocoagulation, may also be effective at recovering these metals. Westerhoff et al. (2015) conducted studies on metal contents found in sludges, and determined recovery potential for metals like gold, copper, silver, iron, palladium, zinc, iridium, aluminum, cadmium, gallium, and chrome.

Many industrial wastewaters associated with the production of military products have a high metal content. These include plating wastewaters associated with small arms ammunition, penetrators, and armor. Nanometals are also being used increasingly in small arms ammunition, penetrators, armor, as additives to uniforms, in explosives formulations, and many other products. Metal recovery technologies would be very valuable for these production activities.

## Products from Digester Gas

As discussed in the energy section above, anaerobic digestion can be used to generate methane for energy use. However, with modified processes and reformulation, it is possible to generate chemical products. With some reformulation, methane can be converted to methanol, a useful solvent, although the economics of this might not be competitive with those from petrochemical sources. And for wastes with high nitrogen content, the reductive process can produce ammonia, which can be stripped as a gas and recovered for use as a chemical product.

## 4 Discussion/Conclusions

### Deriving Energy and Resources from Wastewater fits Army Mission & Doctrine

The production of energy and resources from wastewater treatment is clearly attractive to the Army and other DoD organizations. With processes like forced aeration and sludge handling, wastewater treatment typically consumes a substantial amount of energy. Even if some of this energy could be offset, it could represent a substantial energy and economic savings. In contingency operations, energy production from wastewater treatment could lessen the need for fuel transport, which is costly and dangerous.

### Energy

#### **Anaerobic Digestion is the most applicable technology currently available**

In reviewing the technologies available, it is clear that only one is currently at a stage of development that would allow its use at both types of installations: anaerobic digestion. Technically, sludge incineration could be applied, but its drawbacks preclude its application for most installations or deployed operations. Sludge gasification or pyrolysis could also be applied, but the issues of sludge drying probably exclude their application, except in areas with prolonged, dry heat. Microbial fuel cells, hydrogen producing reactions, and biofuel feedstock-producing treatment are not at a state where they can be applied to treatment at full scale.

Applying anaerobic treatment directly to wastewater using the UASB approach appears to have some great advantages compared to sludge digestion. Wastewater treatment, methane generation, and sludge digestion are all performed in a single reactor, which saves room and costs.

Furthermore, UASBs can be designed to provide tertiary treatment and include nutrient removal by nitrification/denitrification. The entire waste stream is available for methane generation, giving a higher ceiling on gas production. However, UASBs require either extensive modification to most existing wastewater treatment plants, or construction of new plants. Therefore, UASB applications probably are limited to new capital projects.

Sludge digestion could, on the other hand, be applied to existing wastewater treatment plants with modest modifications. However, anaerobic sludge digestion is going against the trend in wastewater treatment at DoD installations, where aerobic digestion is increasingly being used because it has fewer odor problems and can be easier to operate. This inertia would have to be overcome for energy-producing anaerobic sludge digestion to become prevalent at U.S. Army and DoD installations.

Anaerobic digestion does have some areas where focused research could greatly enhance opportunities for use at military installations or for FOBs. Medina et al. (2014b) covers several areas that would be particularly applicable for contingency bases, including development of easier means to monitor performance, investigation of broader substrates that are found at FOBs (such as pulverized paper), and the use of ruminant fecal material as starting seed material. Elbeshbishy et al. (2014) presented interesting results on the use of sonication to boost gas production in anaerobic digestion (the process also boosted hydrogen production in a fermentation reactor).

Research enhancing use of the final product, biogas, could also be valuable. As discussed above, biogas quality is inferior to that of natural gas in terms of methane content (50 to 70% vs. >99%) and in content of undesirable contaminants like hydrogen sulfide. Although biogas can generally be burned sustainably, these features make it a low quality fuel. Simple burners can be designed for efficient biogas use for cooking and heating in the field (Fulford 1996, Kurchania et al. 2011, Walsh et al. 1989). Enhancing the use of biogas can be addressed from two viewpoints. First, by developing a means to use it as it is more efficiently, such as burners that can maximize energy production from the lower methane content and are resistant to corrosion associated from the impurities. Such work would be particularly valuable for contingency base uses. Alternatively, research could focus on further developing an inexpensive and easy-to-maintain means of improving the gas quality, an option that would be very attractive for uses at installations.

Even more advanced work could be applied to reforming methane into hydrogen, which can be used in fuel cells or directly as a clean-burning fuel in vehicles (Medina et al. 2014b, Perez et al. 2006). Such a system has been developed and used at the Sierra Nevada Brewery in Northern

California (Gekas 2009, Sierra Nevada Brewing Co. 2012). Fuel cells provide long-term storage of chemical energy and would serve to concentrate the energy in the biogas, and this process might be an ideal means of energy supply at a CB. A key challenge would be addressing impurities, like hydrogen sulfide, which can poison most fuel cells, but pretreatment approaches could be developed to address that problem.

### **Assessment of other energy producing technologies**

MFCs are not ready for application at installations or for contingency operations. The vast majority of work has been done at the laboratory scale, with only a few pilot studies documented. There does not appear to be a full-scale application to date.

Most MFC applications have used relatively easy-to-biodegrade constituents compared to the less available constituents found in wastewater. Studies with wastewater have not reached the levels of treatment found by modern wastewater treatment plants. However, the treatment levels are in the same order of magnitude, and it does seem reasonable to assume that research will lead to improved designs that will eventually lead to effective treatment.

Treatment of domestic wastewater has also led to less energy production compared to that of substrates like glucose: about 1/3 as much. This really is more of a factor of the wastewater containing largely degraded organic material. Food wastes, which are prevalent at both installations and at contingency bases, could greatly increase energy production.

Another issue with MFCs is that they work best on concentrated wastes, both in terms of treatment and in energy produced. So, as an MFC treats a waste, its effectiveness drops off, and its energy production declines. This is one reason why MFCs have not been able to meet treatment standards and have not been able to achieve high energy recoveries. This problem exists in all biological treatment systems, but most wastewater systems are able to address this by using sludge recycling or similar strategies.

MFCs have properties that make them attractive for further development. First, an MFC system would be best applied to concentrated wastes. Water conservation is now being widely practiced throughout the DoD and the United States. This produces more concentrated wastes, which will fit well into MFC treatment. MFCs produce little sludge, which is desirable from a materials handling perspective. And MFCs produce electricity directly, so

they may turn out to be ultimately more efficient than anaerobic digesters due to the inefficiency of gas combustion.

One way to accelerate the applicability of MFCs is to use them in conjunction with other treatment technologies. If an MFC was used in series with a conventional wastewater treatment technology, such as activated sludge, the MFC could be focused on energy production and pretreatment, and the follow-on treatment could be then used to complete the treatment.

Assuming that current research investment continues or grows, it seems reasonable to assume that full-scale MFCs will be available within the next 5 to 10 years. However, a small reactor could be developed for use at small operational bases (on the order of 20 to 50 men). The reactor would have only one goal, to generate supplemental electricity to augment or recharge batteries. It would use black water and other organic wastes (particularly waste food) to do so. Such a reactor could be developed within 2 or 3 years. The newly published work on the AnEMBR appears to be a significant breakthrough that could accelerate the adaptation of MFCs for effective wastewater treatment and energy production (Katuri et al. 2014).

Hydrogen-producing reactions also have some key obstacles to overcome to become a viable technology to apply either at installations or in contingency operations. To date, studies have demonstrated gas production and degradation of organic compounds, but more often than not, the reactions have had a rather inconsistent performance. Applications to wastewater have been conducted in the laboratory, but the focus has been on promoting gas production as opposed to effective treatment. However, hydrogen is a very attractive fuel, as it has a very high energy density and burns very cleanly. Hydrogen is also used in most modern day fuel cells, which are being studied as a viable means of energy production for the Army. Because of these features, a wastewater treatment system that produces this fuel would be very valuable to the Army and the DoD.

Cultivating biofuel stock in wastewater treatment reactors has some of the same attraction and challenges as producing hydrogen producing microorganisms. It is attractive because wastewater would provide a free food source space for stimulating these microorganisms. However, algal systems would require a good deal of space, and would be most applicable to nutrient treatment. Genetically modified bacteria might eventually be applied to wastewater treatment reactors, but this appears to require much



more research work. Unlike hydrogen production, which could be directly used by an installation or contingency base, biofuel stock would have to be collected and refined. This scenario would be less attractive for installations and would not be feasible for a contingency base.

## **Combining Technologies**

Combining these technologies might result in still further benefits. MFC would be a perfect initial technology to apply to concentrated wastes. This could be followed by UASB for wastewater treatment and to generate biogas. Residual sludge could be anaerobically digested or processed in a gasifier (or both). Other combinations are possible; Logan (2008b), for example, has studied MFC systems that also produce hydrogen gas. Coupling energy production and resource recovery also appears feasible, and could be explored in the future.

## **Effects on Waste, Water, and Climate Change**

If properly applied, most of these technologies have the ability to have beneficial effects on waste minimization, water reuse, and climate change. For example, anaerobic sludge digestion produces a sludge material suitable for land application, either directly or in compost. MFCs and UASB produce less sludge than processes like activated sludge. Consequently, it is possible that energy-producing wastewater treatment could reduce solid waste generation associated with sludge management.

Energy recovery from wastewater could also create opportunities for enhanced water reuse and recycling, primarily by providing energy for processes like nanofiltration or reverse osmosis. Promoting more water reuse can reduce the amount of raw water that needs to be conveyed to an installation or contingency base, which may result in even more energy savings.

Finally, the generation of energy from wastewater can also contribute to lower overall greenhouse emissions. Carbon emissions from organic material in wastewater are part of the earth's carbon cycle. Even landfilled sludges eventually degrade, forming carbon dioxide and methane. Extracting the energy from this organic material simply accelerates this process, and in doing so, promotes more efficient conversion to carbon dioxide over methane. This is advantageous, since methane is about 20 times more potent a greenhouse gas than carbon dioxide over a 20-year

period (USEPA 2014). However, energy generated from such systems offsets energy needed from fossil fuels, resulting in a net reduction in greenhouse gas emissions. This offset may become very valuable over time, as these emissions become increasingly regulated, and the DoD has taken a proactive role in setting goals for greenhouse gas reductions (U.S. DoD 2013).

## **Resource Recovery from Wastewater Treatment**

### **Sludge and sludge-derived products**

Resource recovery from wastewater treatment is a developing process that is increasingly being implemented. The most basic resource found in wastewater is nutrients. The most common way to recover those nutrients are sludge utilization approaches, which include direct application of dried or semi-dried sludge, digested sludge to soil, or the incorporation of the sludge in compost. These materials have been commonly used as soil amendments — as fertilizers and as a means of improving soil stability and water-holding capacity.

However, biosolids have lower nutrient densities than mined or petrochemically derived fertilizers. Therefore, these may not be attractive as fertilizers for high-value agricultural or gardening applications. Any strategy to reuse these materials must take into account whether there is a commercial demand for these materials. Furthermore, since the current value of nutrients in biosolids (\$8 per ton) is a fraction of the transport costs (\$30 per ton to transport 50 km in the U.S.), nutrient recovery via biosolids can be very expensive if they can't be locally used. Finally, military installations have rules that limit their competition with private enterprise, which may limit their ability to sell or even give away sludge and sludge-derived products.

Some of these issues can be addressed if these products are used on-site — for parade grounds, golf courses, sports fields, and for range management. Many installations have a great deal of land that requires landscaping and maintenance, and the supplementary source of soil amendments can reduce costs to the installation and to the Army in general.

Military installations, on the other hand, can also use sludge-derived additives directly on sports fields, parade grounds, park areas, and for range management (Medina et al. 2013). These uses can offset the need to

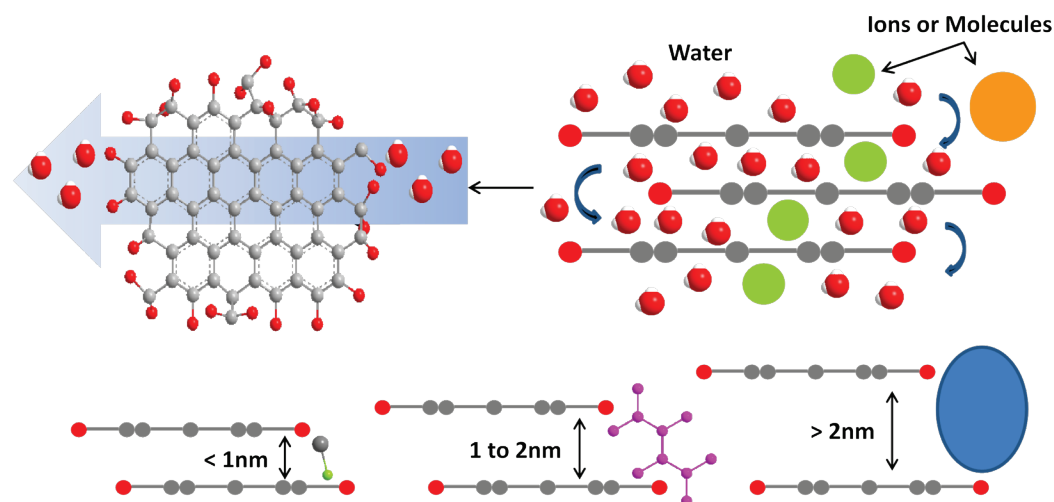
purchase fertilizer, and could be a beneficial diversion as part of a net zero waste program.

Although it is feasible to implement direct sludge incorporation into soil, composting appears to be the most efficient for several reasons. First, it quickly stabilizes the volatile components of the sludge, minimizing odor issues. Second, it is well established and relatively easy to do, particularly compared to anaerobic digestions. Third, compost can also tie in other waste components, such as food waste, paper, wood, and yard waste, thereby addressing several key waste streams.

### Advanced Resource Recovery

Improvements in extractive methods based on size exclusion with sieving membranes are developing. One very promising technology is graphene oxide (GO) membranes (Joshi et al. 2014; Mi 2014). Graphene oxide sheets can be deposited upon each other using methods like vacuum filtration or layer-by-layer assembly to form channels so small that only water molecules can pass through them, and the surfaces are so smooth that friction is minimal, reducing operating pressures and allowing for fast treatment. Furthermore, the recovery can be tuned by applying ionic or organic spacer to the sheets to target specific metals or organic compounds. Figure 8 shows separation of ions and molecules in precise size distributions by tuning the GO layer spacing. This approach offers selective extraction of target resources from wastewater streams.

Figure 8. Conceptual water purification design representing graphene oxide filtration and preparation (adapted from Mi 2014).



Recovery of nutrients into concentrated chemical nutrient products may ultimately expand the use of nutrient recovery from wastewater. Products such as struvite, calcium phosphate, iron phosphate, phosphoric acid, ammonium sulfate, and ammonium nitrate can also be recovered, depending on the nature of the wastewater. These products could be made into high value fertilizers and most of these compounds have use in alternative industries. Recovery of polymers for bioplastics and other applications could eventually be routinely recovered from wastewater.

The authors' research indicates that advanced resource recovery is more highly developed in Europe, although some progress is also being made in the United States. Extractive techniques, although technically feasible, are not economically competitive at this time (WERF 2010), although it has been argued that the greatest obstacle to more widespread implementation is the commitment to sustainability in the wastewater industry (Guest et al. 2009; Satterfield et al. 2009). Separation technologies make nutrient recovery economically possible, but acceptance issues remain; nutrient recovery would also require changes in plumbing and collection that would greatly increase costs. Consequently, it seems that application of resource recovery for wastewater treatment plants in military installations is not practical at this time.

However, as time goes on, resources are expected to increase in cost. Phosphorus, for example, is generally mined from a limited number of sites, and it could increase in cost in the future (WERF 2011, The Johnson Foundation 2014). At the same time, resource recovery wastewater is a developing area, and it seems likely that extractive costs will decrease over time. Another factor is that regulatory requirements for nutrients and other contaminants are expected to become more stringent (WERF 2011). Recovery of nutrients and other chemicals could reduce eutrophication effects and other contamination issues (The Johnson Foundation 2014) and certain reactive nitrogen forms (particularly nitrous oxide,  $N_2O$ ) are significant greenhouse gases. Environmental issues and policy are also driving forces that may encourage resource recovery. Resource recovery may also be incorporated as part of treatment to recover water from wastewater.

The Hampton Roads Sanitation District reportedly recovers 85% of the phosphorus and 25% of the ammonia in its sludge dewatering process; these chemicals are then used in the commercial product, Crystal Green

(<http://www.crystalgreen.com/about-crystal-green>). This demonstrates that resource recovery is possible on a commercial basis (NACWA 2013). There is increasing motivation to redefine wastewater treatment plants as water resource recovery facilities (WRRFs) (The Johnson Foundation, NACWA 2013). Therefore, although advanced resource recovery does not appear to be viable for military installations at this time, the Army and the DoD should continue to monitor progress of research and applications.

## **Economy of Scale**

Earlier in this report (see section “Wastewater and the DoD”), the authors identified three massive installations with populations exceeding 60,000 residents and workers. Such an installation is comparable to a large town and opens the door to a wide range of advanced options for enhancing wastewater treatment. However, these scales are dwarfed by the wastewater systems found at the larger cities in the United States. For example, Perez et al. 2006 evaluated several Army installations with the potential to generate relatively large volumes of anaerobic digester gas based on the wastewater flow. Ft. Stewart was one of the larger producers of wastewater with a plant designed for 9 mgd, and an actual flow on the order of 5 mgd. The Hyperion Sewage Treatment Plant in Los Angeles, CA ([http://www.lacitysan.org/lasewers/treatment\\_plants/hyperion/index.htm](http://www.lacitysan.org/lasewers/treatment_plants/hyperion/index.htm)) treats wastewater generated by over a million people as well as related industries, and has a flow on the order of 350 mgd, nearly 40 times larger than the design flow and 70 times larger than the actual flow. This massive size allows for economic recovery of energy and resources at a scale far beyond what could be found at military installations. These limitations might be addressed by teaming with municipalities and industries to create a larger wastewater pool from which to obtain resources. However, for now, ERDC should focus research on technologies that could be economically applied to smaller treatment plants on the order of 3 to 10 mgd.

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14. ABSTRACT <p>This report summarizes a study to assess energy and resource recovery from wastewater treatment and assess short- and long-term opportunities and impacts for the Army and the Department of Defense (DoD) in general. The organic material in wastewater contains inherent energy. The challenge is concentrating and recovering this energy. Several methods are available; of these, anaerobic digestion (either of the sludge, or directly applied to the wastewater using Upflow Anaerobic Sludge Blanket or a similar reactor) is the most advanced and can be readily applied to existing military installations or to contingency operations.</p> <p>Recovery of chemical products is another option for wastewater treatment. The most commonly recovered products are nutrients, in the form on nitrogen (N) and phosphorus (P). The simplest way is to recycle the collected and digested biosolids (sludges), either for direct soil application or by incorporation into compost. Resource recovery from wastewater may eventually include biopolymers that could make bioplastics or valuable nanometals that are increasingly found in consumer products.</p> <p>Many of the energy recovery technologies and most of the resource recovery approaches (beyond simple biosolids recovery) require large-scale operations to be economically viable at this time. Wastewater treatment facilities that serve Army and other DoD installations tend to be relatively small, limiting the application of many approaches that might be viable in the civilian sector. ERDC should focus research on technologies that could be economically applied to smaller treatment plants on the order of 3 to 10 mgd.</p>					
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